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Pilot Scale Process Evaluation of Reburning for In-Furnace NOx Reduction

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PILOT SCALE PROCESS EVALUATION OF REBURNIN(FOR IN-FURNACE NO_x REDUCTION

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16. ABSTRACT The report gives results of coal and natural gas reburning application tests to a pilot scale 3.0 MWt furnace to provide the scaling information required for commercial application of reburning to pulverized-coal-fired boilers. Initial parametric studies had been conducted in a 23 kWt bench scale reactor to quantify the impact of fuel and process parameters on reburning effectiveness. The results of this investigation confirm the potential of the reburning process for significant NOx reduction. Process effectiveness depends strongly upon the NOx and O2 concentrations at the end of the main heat release zone; the stoichiometry, temperature, and residence time in the fuel-rich reburning zone; the fuel composition and mixing of the reburning fuel jet; and the temperature of the final burnout zone. This investigation also identifies and defines the optimum design criteria for reburning application and demonstrates that it is possible to scale up the process without losing effectiveness. In addition, it shows that simultaneous NOx/SOx reductions of up to 60% can be achieved with reburning combined with sorbent injection.

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Pulverized Fuels	Reburning	21D
Natural Gas		
Sulfur Oxides		
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ABSTRACT

Reburning, as applied to pulverized coal fired boilers, involves the injection of a secondary fuel above the main heat release zone to produce a reducing zone which acts to convert NO_x to molecular nitrogen. Overfire air is added above the reburning zone to complete the combustion. Initially parametric studies were conducted in a 25 kW bench scale reactor to quantify the impact of fuel and process parameters on reburning effectiveness. These studies were subsequently supported by pilot scale testing in a 3.0 MW furnace to provide the scaling information required for commercial application of reburning under highly varied industrial conditions.

The results of this investigation confirm the potential of the reburning proces for significant NO_x reduction. Process effectiveness depends strongly upon the NO_x and O_2 concentrations at the end of the main heat release zone; the stoichiometry, temperature, and residence time in the fuel-rich reburning zone; the fuel composition and mixing of the reburning fuel jet; and the temperature of the final burnout zone. This investigation has also identified and defined the optimum design criteria for reburning application and demonstrated that it is possible to scale up the process without loss in effectiveness. In addition, it has shown that simultaneous NO_x/SO_x reductions of up to 60 percent can be achieved with reburning combined with sorbent injection.

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1.0 INTRODUCTION

Since it was first recognized that nitrogen oxides (NO_x) emitted by stationary sources made a significant contribution to the degradation of air quality, there have been considerable advances in control technology to reduce emissions. NO_x control technologies fall into two categories: those which prevent the formation of nitric oxide (NO) and those which remove NO from the products of combustion. Nitric oxide is formed during combustion either from molecular nitrogen or from nitrogen contained in the fuel. Modification of the combustion process to change peak temperatures and maximize residence times under fuel-rich conditions minimize NO_x formation from both of these sources. Consequently, provided the process requirements are satisfied, combustion modification provides a cost effective method of controlling NO_x emissions. However, when the process is not tolerant to combustion modification or very low emission levels are required it may be necessary to use flue gas cleaning techniques to remove NO_x from the combustion products. This report addresses a technology which removes NO from combustion products using fuel as the reducing agent and involves similar kinetic processes to those involved in combustion modification techniques. This technology is variously referred to as:

- In-furnace NO_x reduction
- Reburning
- Staged fuel injection
- "MACT"

Reburning can be considered as the process which allows "in-furnace NO_x reduction" to take place.

1.1 Background

Reburning for in furnace NO_x control is currently being developed by a number of organizations primarily in Japan and in the United States. The term reburning denotes the process by which a fraction of the fuel from the main heat release zone is redirected to a zone downstream of the main zone. The fuel is injected downstream to form an overall oxygen deficient region referred to as the reburn zone. Additional air is added even further downstream to complete combustion. This process therefore forms three zones: (i) the main heat release or primary zone, (ii) the oxygen starved reburn zone and (iii) the burnout zone wherein combustion is completed. Figure 1-1 shows a schematic of the reburning process as it might be applied to a real boiler.

- Primary Zone. This main heat release zone accounts for approximately 80 percent of the total heat input to the system. operating under fuel lean conditions, the primary zone produces the initial NO_x species.

- Reburning Zone. Reburning fuel is injected downstream of the primary zone to create a fuel-rich mixture. Three major general reactions take place in the reburning zone which affect the reburning process:

    1. NO reacts with hydrocarbon radicals by reactions such as

    $$\begin{aligned} NO + CH &\longrightarrow N + CHO \\ &\longrightarrow HCN + O \end{aligned}$$

       which increases the nitrogen radical pool.

    2. Interconversion of nitrogen species among different fixed nitrogen compounds (NO, HCN, or NH_3). (In this report, the expression XN is used to refer generically to any of these three fixed nitrogen species.)

    3. The formation of molecular nitrogen by the reaction of nitrogen radicals with NO. The reaction:

    $$NO + N \longrightarrow N_2 + O$$

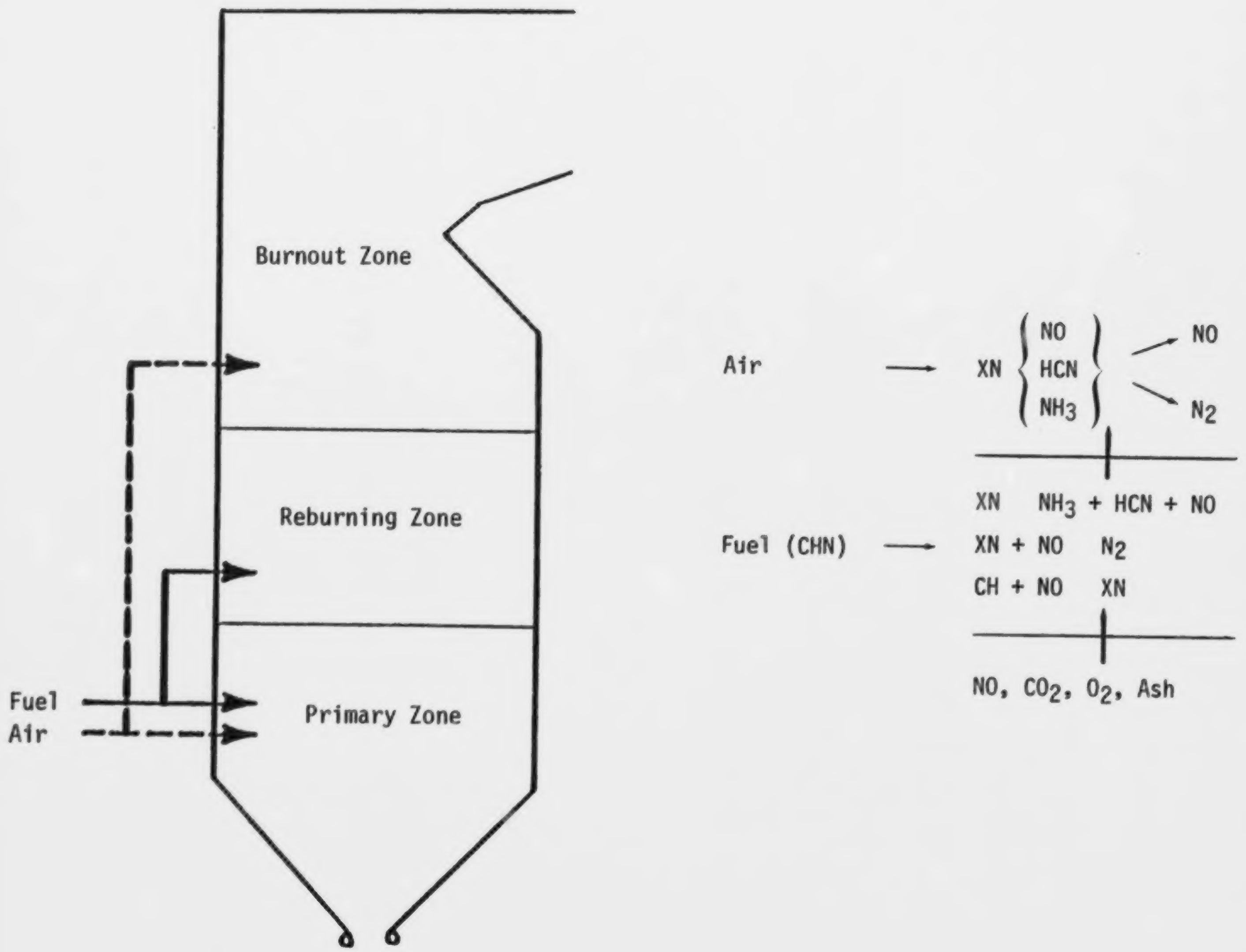

Burnout Zone
Reburning Zone
Primary Zone
Fuel
Air
Air
XN
NO
HCN
NH_3
NO
N_2
Fuel (CHN)
XN NH_3 + HCN + NO
XN + NO N_2
CH + NO   XN
NO, CO_2, O_2, Ash

Figure 1-1. The reburning process.

sometimes referred to as the "back-Zeldovich" reaction mechanism, is the most probable path although reactions with NH_i species are possible. Consequently, the nitrogen oxide formed in the primary zone is converted either to N_2, NH_3, HCN, or retained as NO. When the reburning fuel contains nitrogen (e.g., if the reburning fuel is coal), coal nitrogen could remain with the char orf form NO, HCN, and NH_3. Thus, the products of this zone contain nitrogen species which can be converted to NO, namely char nitrogen, NH_3, and HCN, as well as NO. The sum of these gas-phase species is referred to as total fixed nitrogen (TFN).

- Burnout Zone. In the burnout zone, air is added to produce overall fuel-lean conditions which oxidize all the remaining fuel. The TFN or char nitrogen is either converted to NO or partially to N_2. Emissions are minimized as the TFN conversion is minimized and this zone is analogous to the second stage of a staged combustion process. Combustion must be completed efficiently, but the ultimate NO_x levels must be minimized.

The basic concepts associated with in-furnace NO_x reduction by reburning are not new. The reduction of NO by flames has been appreciated for over a decade. A flue gas NO_x incinerator was developed by the John Zinc Company (Reed, 1969). The term "reburning" was coined by Wendt, Sternling and Matovich (1973) who reduced NO produced in a laboratory scale flat flame by adding methane or ammonia to the combustion products. The EPA and more recently GRI have supported detailed studies on the application of reburning technology to U.S. designed boilers. The work has been directed to date at the impacts of process parameters and were carried out at bench scale facilities (Chen, et al., 1982; Greene, et al., 1984;; Seeker, et al., 1985). These studies have shown that the reburning zone (between the point of reburning fuel and the burnout air introduction) should be as large and as hot as possible and that an optimum stoichiometry exists at 0.9 that minimizes NO_x emissions. These studies also reveal that it is more difficult to reduce NO_x by reburning with fuel containing fuel nitrogen if the starting level i.e., the NO_x from the main burner zone, is low. However, reburning with natural gas was capable of achieving reductions at much lower levels of NO_x (less than 200 ppm). The impacts of other parameters such as reburning coal type, stoichiometries of each zone, temperatures in the burnout zone, transport media for reburning fuel (air vs. flue gas) and rate of fuel and air mixing were also independently investigated in these experiments. Other laboratory studies carried out recently include the application of reburning to process heaters and cement kilns (Yang, et al., 1984) and firetube package boilers (Mulholland and Lanier, 1984).

Recently, Japanese investigators have reported the application of reburning to large test furnaces (Takahashi et al., 1981; Sekiguchi et al., 1984; Miyamal et al., 1985). The MACT (Mitsubishi Advanced Combustion Technology) in-furnace NO_x removal process first applied the concept of reburning to a full scale boiler. It is claimed that the NO_x produced by the main firing system can be reduced "to half at any level of concentration," (Takahashi et al., 1981). However, recent results obtained on the bench-scale Control Temperature Tower (CTT) at EER indicate that the effectiveness of the reburning concept depends heavily on primary NO_x levels (Greene et al., 1984) as well as those parameters mentioned earlier.

1.2 Purpose and Scope

The impacts of process parameters on the effectiveness of reburning had been defined in the bench scale investigation (Greene, et al., 1984). The purpose of this program was to evaluate the influence of scale on the effectiveness of reburning; particularly, the impacts of mixing. The ultimate goal was to provide scaling information and generate design and operation guidelines for the application of reburning in a full-scale boiler.

In order to accomplish these objectives, the program was divided into five tasks which are described below:

1.2.1 Task 1--Facility Characterization

This first task includes the design and construction of the facility and the initial shakedown tests necessary to characterize the furnace and bring it up to a data taking mode. The pilot scale Reburning Tower, which had a firing capacity of 10 million Btu/hr, was designed to be large enough for examining the effects of mixing by employing the scaling criteria for jet mixing in a cross flow. At the beginning of the program, all of the systems were checked out to ensure tha they operated properly and safely. Mass balances, correct interfacing of the new computer program, temperature profiles, and burner characterization studies were typical tests carried out during the shakedown period.

1.2.2 Task 2--Evaluation of Impact of Scale on Process Parameter Effects

The purpose of this task was to examine the effects of scale on the major process parameters that have been demonstrated to influence the reburning process (Greene, et al., 1984). The detailed results of this task are presented in Chapter 4.0.

1.2.3 Task 3--Reburning Zone Mixing Studies

The overall purpose of this task was to examine the effects of reburning zone mixing on the reburning process and to generate guidelines for full-scale application. With recirculated flue gas as the reburning fuel transport medium, major variables investigated included jet velocity and penetration, and the configuration of the jets. A detailed mapping of the reburning zone was completed to add insight into NO reduction mechanisms. Detailed results of Task 3 are presented in Chapter 5.0.

1.2.4 Task 4--Process Optimization

Since the baseline conditions of the pilot scale Reburning Tower may not be applicable to a particular boiler, the intention of Task 4 was the optimization of the reburning process for a variety of operating conditions.

The use of air as reburning fuel transport medium was studied, as well as the effects of the primary fuel and reburning fuel. Results of this task are presented in Chapter 6.0.

1.2.5 Task 5--Combined Process

The examination of the feasibility and effectiveness of multiple-staged reburning were the objectives of Task 5. Systems studied included a staged plus reburning process, and a dual reburning process, where two consecutive reburning zones were employed. Results were compared with those obtained from the standard reburning process and are presented in Chapter 7.0.

1.2.6 Task 6--Data Analysis and Reporting

The objective of this task was to review the data generated in the other five tasks in order to provide recommendations and direction for the testing. This task was to be ongoing throughout the course of the project, resulting in data reduction and assimilation, monthly progress reports, and finally this report.

2.0 EXPERIMENTAL FACILITIES

2.1 Design Considerations

The design objective for the pilot scale reburning tower was to simulate combustion conditions typical of United States designed pulverized coal-fired boilers in order to generate guidelines for process parameters and reburning zone mixing effects for full scale applications. In addition, the combustor system must exhibit sufficient flexibility such that specific combustion conditions may be varied. Design considerations included:

- Total firing rate of 10M Btu/hr with up to 30 percent of total load introduced in the reburning zone.
- Flexibility of location and configuration of reburning and burnout air injectors.
- Ability to vary jet diameter, velocity, and penetration across the furnace.
- Duplication of typical time/temperature histories of utility boilers and the ability to alter the thermal profile.
- Ability to employ either air or recycled flue gas as reburning fuel transport medium.
- Ability to maintain turbulent flow in the furnace for mixing purposes.
- Ability to fire either gaseous or solid fuels as primary and reburning fuels.
- Duplication of typical utility boiler entrainment rates and jet velocity to cross-stream velocity ratios for the injection of reburning fuel and burnout air.

In chemically reacting systems, it is usually impossible to maintain all similarity conditions. For example, the requirement that residence times be equal is not compatible with the equality of Reynolds numbers. Consequently, the concept of partial modeling has arisen and these principles may be applied to the process of reburning. The critical feature of reburning is the injection of fuel into hot combustion gases. Maintaining similarity in the injection process is of primary concern and can be accomplished if the ratios of source momentum flux to shear force are equal for model and prototype combustion systems (Beer, et al., 1972). In cases where the density ratios are equal, then the criteria that momentum fluxes should be equal, reduces to a simple ratio of velocities for the jet relative to the cross stream. As an alternative or supplement to maintaining mass flux ratios, the relative rate of mixing or entrainment of the reburning jets with the main stream can be considered. Particularly, similarity can be maintained if the ratio M_e/M_s is equal for the model and boiler (Ricou, et al., 1961), where

M_e = the mass entrained by the jet per unit time,
M_s = the mass flow rate of the main stream

This ratio can be determined as a function of jet diameter, jet trajectory, and the ratio of the jet and stream densities. Reburning injector design and configuration were based on the criteria listed above and on empirical correlations developed for calculating jet trajectory and penetration (Shandarov, 1957). The key issue in this portion of the design was versatility and the ability to simulate a variety of injection schemes and jet penetration depths. A schematic diagram of the furnace and support facilities is shown in Figure 2-1.

2.2 Reburning Tower

The reburning tower was a down-fired furnace, with inside dimensions of 4 x 4 x 26 feet. A schematic of the furnace is presented in Figure 2-2. Ten thermocouple ports were located at various positions down the length of the furnace. Figure 2-2 shows the locations of the seven levels of reburning or

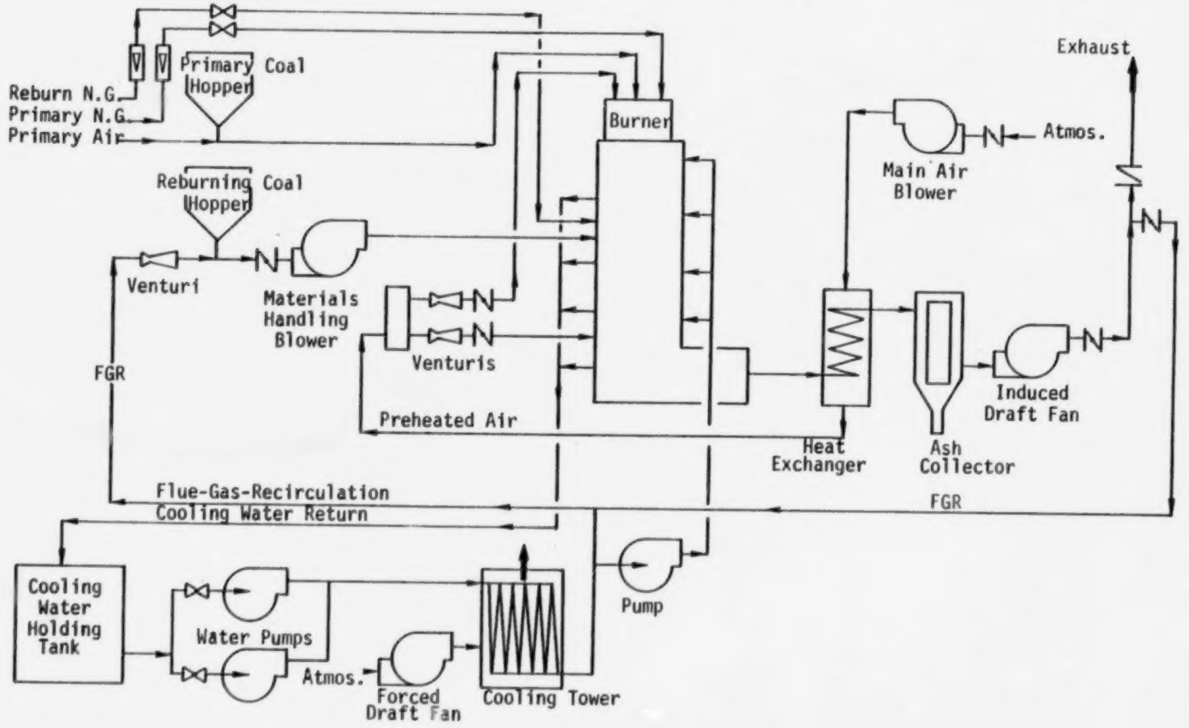

Reburn N.G.
Primary N.G.
Primary Air
Primary Coal Hopper
Reburning Coal Hopper
Venturi
Materials Handling Blower
Venturis
FGR
Burner
Preheated Air
Flue-Gas-Recirculation
Cooling Water Return
Main Air Blower
Atmos.
Exhaust
Heat Exchanger
Ash Collector
Induced Draft Fan
FGR
Cooling Water Holding Tank
Water Pumps
Atmos.
Forced Draft Fan
Cooling Tower
Pump

Figure 2-1. Flowsheet of the experimental facility.

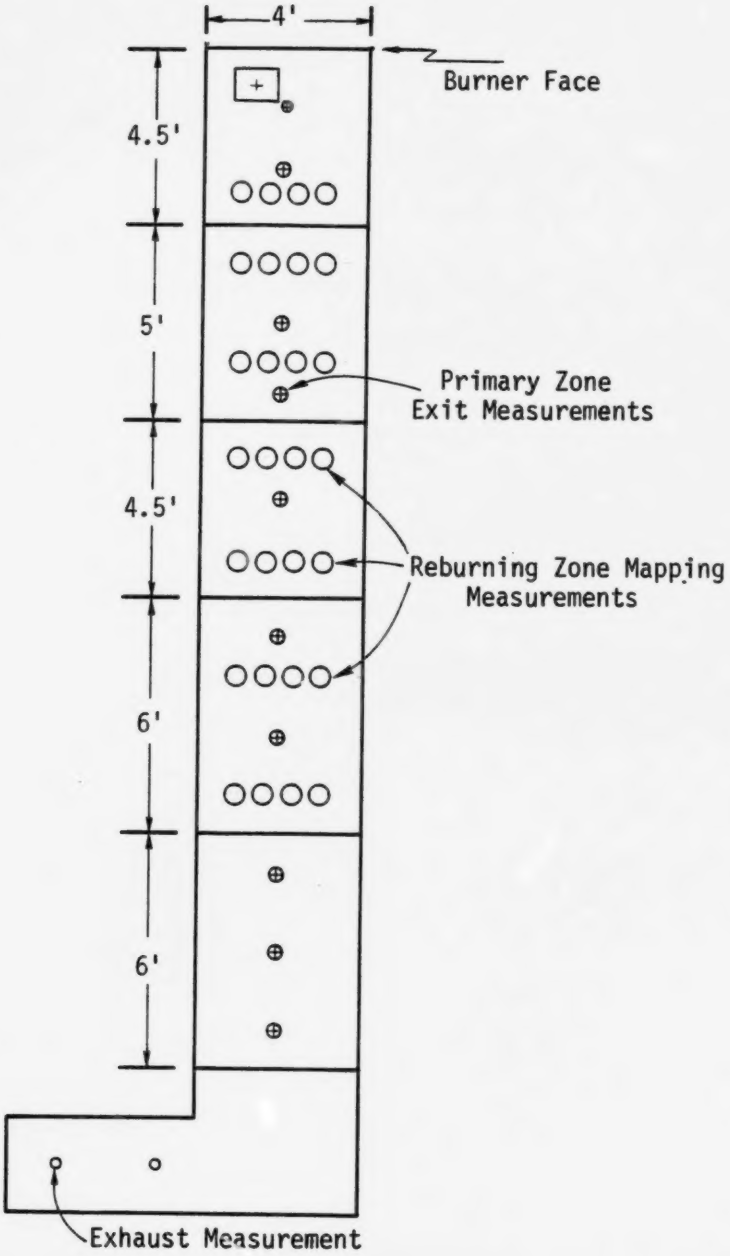

4'
Burner Face
4.5'
5'
Primary Zone
Exit Measurements
4.5'
Reburning Zone Mapping
Measurements
6'
6'
Exhaust Measurement

Figure 2-2. Reburning tower schematic.

burnout air injection ports, numbered 1 through 7 from the top of the tower. The levels ranged from 3.5 to 19 feet from the burner face. Each level had two identical opposed sides consisting of four 6-inch ports. On the front and back faces of the furnace, each level had two 6-inch ports located at the same relative position as the outer ports on the aforementioned sides. A 9-inch port was located in the center of the front face. A 4 x 14 inch viewing slot occupied the center of the back face. The injector module is illustrated in Figure 2-3. The reburning tower was fabricated with a 1-inch cooling water jacket. The top three sections of the furnace were cast with 3-inches of 3400°F Greencast-94 refractory. Sections 4 and 5 were cast with 3-inches of 2700°F Kast-Set refractory. Manipulation of the temperature profile was possible by insertion of cooling panels. The panels were fabricated with 1-inch OD stainless steel tubing. Each panel had a surface area of 38 square feet.

2.3 Burner

The main burner design was based on a previous jet burner design developed at EER and generated relatively uniform velocity and composition profiles across the furnace. A layout of the wall-fired burner employed for testing is presented in Figure 2-4. Four identical nozzles with 6-inch throats were used. Two concentric stainless steel pipes for primary air/fuel transport were located in the center of each throat. The inner pipe, which has a 1.45 inch OD, was used for axial injection of the primary air and coal, when coal was utilized as the primary fuel. A spinner was positioned at the exit of the pipe to induce swirl in the primary air. This pipe was encircled by another with a 1.88 inch OD. The annular space between the two pipes was used for the transport of natural gas when it was the fuel of choice. The natural gas was injected radially into the furnace through ten 0.375 inch diameter holes spaced evenly around the circumference of the outer pipe. Preheated secondary air was injected radially into the nozzle throats via a windbox four feet in diameter. Five swirl vanes, each covering 120°, were located in the annulus between the fuel injector and nozzle wall to ensure thorough mixing between the air and fuel. To enhance the establishment of a one dimensional flow pattern, the entrance to the furnace included a 4.5 inch

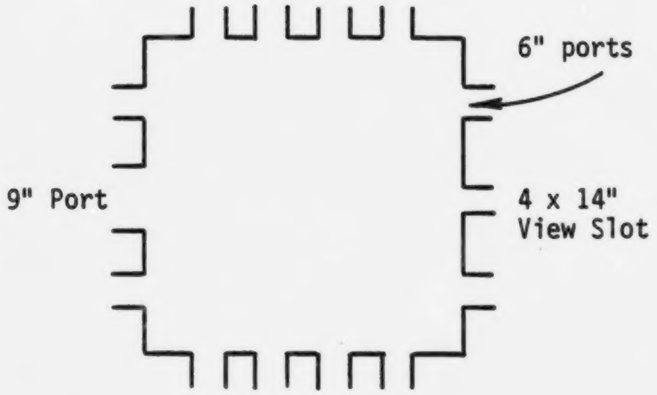
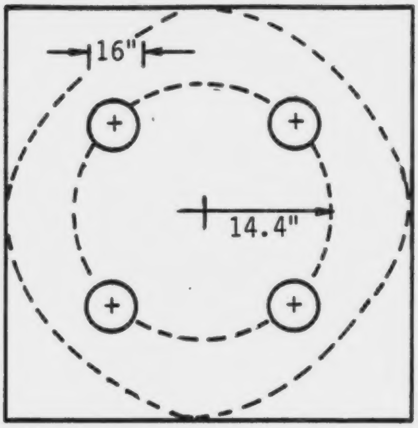

6" ports
9" Port
4 x 14"
View Slot

Figure 2-3. Injector module for reburning fuel or burnout air.

- Nozzle Layout



- Nozzle Schematic

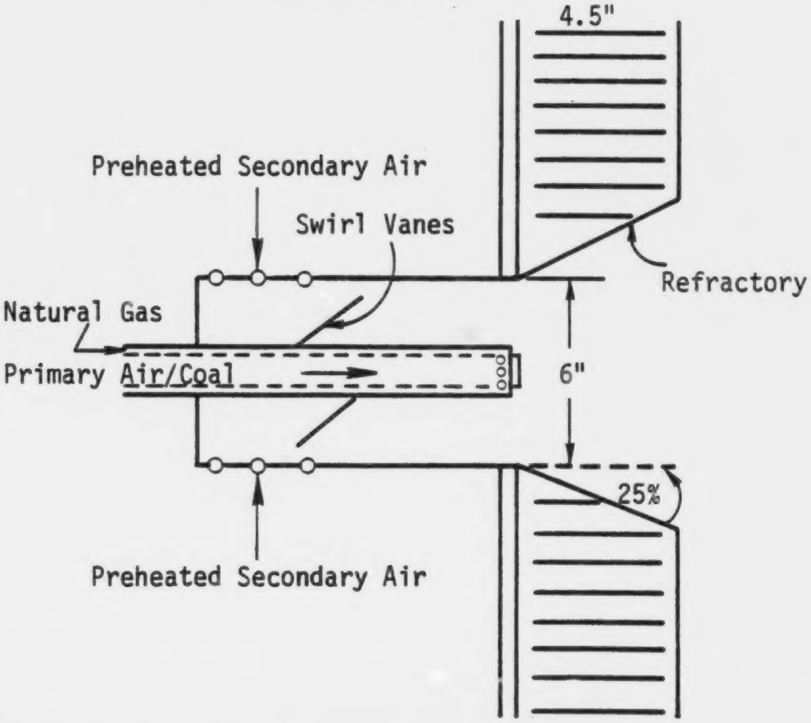

4.5"
Preheated Secondary Air
Swirl Vanes
Refractory
Natural Gas
Primary Air/Coal
6"
25%
Preheated Secondary Air

Figure 2-4. Main burner injection scheme.

long quarl which diverged from 6.0 to 10.2 inches. This burner produced essentially a one-dimensional, plug flow flame with no backmixing.

2.4 Support Facilities

2.4.1 Exhaust, Flue Gas Recirculation and Air Delivery System

A schematic of the Reburning Tower exhaust, flue gas recirculation, and air delivery system is shown in Figure 2-5. The exhaust system and air delivery system of the Reburning Tower were coupled with the respective systems of the existing Small Water Tube Simulator (SWS) furnace. After exiting the ashpot of the furnace and passing through the shell of the SWS, the Reburning Tower exhaust passed through a heat exchanger where the exhaust gas preheated the combustion air for the furnace. The effluent from the heat exchanger was cleaned of fly ash by passage through a baghouse. The baghouse was exhausted with an induced draft (ID) fan, and the clean exhaust was discharged through the exhaust stack or partially recirculated for use as the reburning fuel transport medium. The ID fan was equipped with a damper, and the furnace was generally run at ambient or slightly positive pressure to prevent dilution by in-leakage of air.

Recirculated flue gas was carried by a duct which branched off of the exhaust stack directly above the ID fan. A materials handling blower located downstream of the reburning coal injection point created the pressure drop necessary to induce flow in the duct. An air lock system at the coal injection location allowed the reburning coal to be introduced into a positive pressure transport line. Dampers were present in the stack and the FGR duct to regulate the gas flow. The flow was measured upstream of the coal injection point by a venturi flowmeter. The pressure drop across the element was converted to a numerical value of SCFM by a pressure transducer and input to a continuous data reduction system. After injection of the reburning coal into the air lock and passage through the blower, the stream was fed from ground level to its point of injection into the furnace. An elbow located near the exhaust stack could be removed to allow the use of air as the re?urning fuel transport medium.

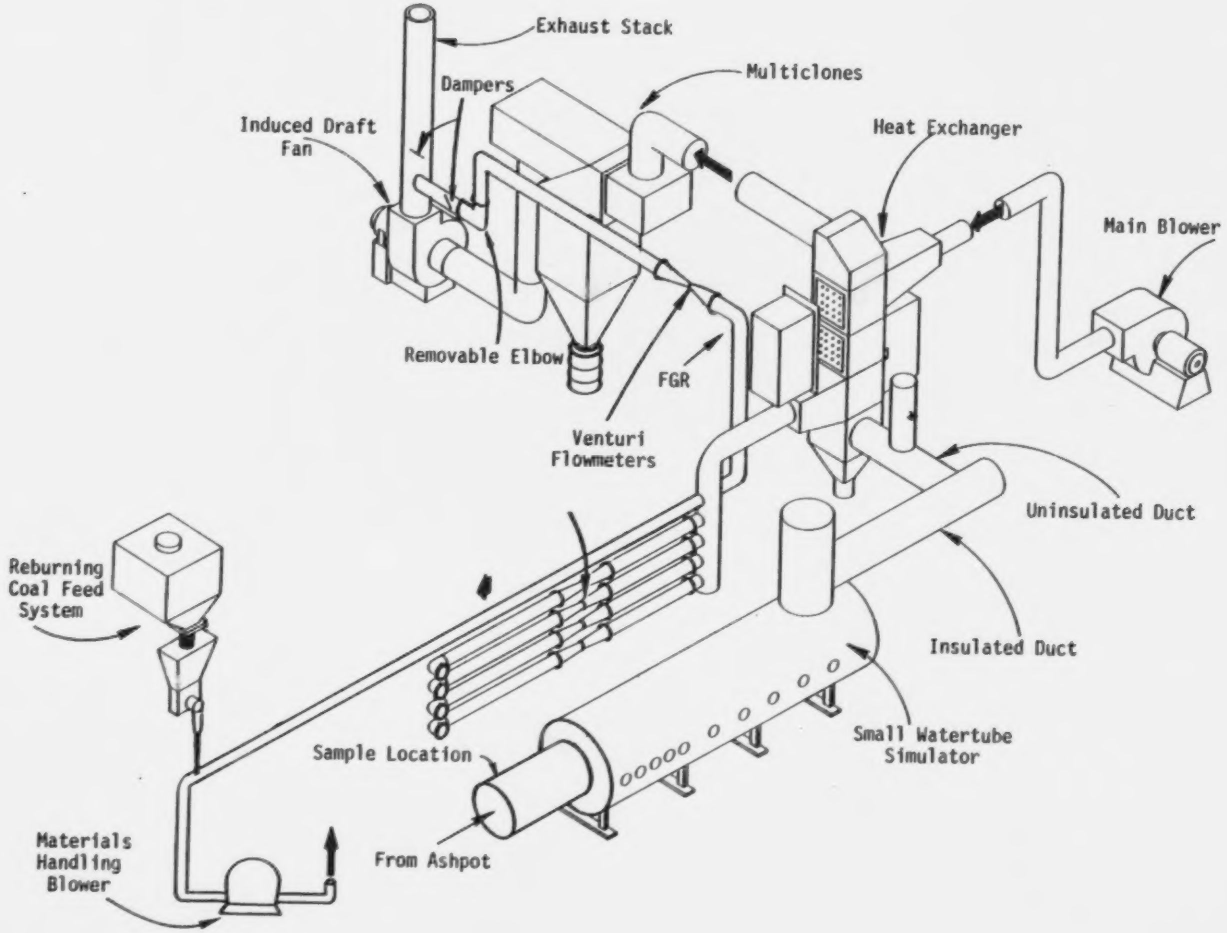

Exhaust Stack
Multiclones
Dampers
Induced Draft Fan
Heat Exchanger
Main Blower
Removable Elbow
FGR
Venturi Flowmeters
Uninsulated Duct
Reburning Coal Feed System
Insulated Duct
Small Watertube Simulator
Sample Location
Materials Handling Blower
From Ashpot

Figure 2-5. Component of the reburning tower exhaust, flue gas recirculation, and air delivery systems.

The Reburning Tower air delivery system was comprised of a forced draft fan, the aforementioned preheater, an air distribution plenum, venturi flowmeters, and metering values. After passage through the preheater via the main blower, the furnace combustion air entered a plenum. Four separate air streams, two for use as primary combustion air, one for burnout air, and the other for staging air in multi-staged systems, exited the plenum. Flow rates of the streams were controlled by the metering values, and the method of flow rate measurements was identical to that of the reburning fuel transport gas.

2.4.2 Water Recirculation System

The cooling water requirements for the Reburning Tower were supplied by closed-loop water recirculation system. Water at a pressure of about 35 psi was pumped up one leg of the platform as a supply manifold. Cooling water for the cooling jacket and cooling panels was taken off the supply manifold and dumped into another leg for the return manifold. The hot water was returned to an automatic cooling tower and then recycled through the system.

2.5 Measurements

A brief description of the routine measurements is given in this section. More detailed information on measurements and the instruments used during testing can be found in Appendix B.

2.5.1 Gas Sampling System

Concentrations of THC, NO_x, CO, CO_2, and O_2 were measured at the reburning tower exhaust duct, as was shown in Figure 2-2, as well as at upstream locations in the furnace if desired. A stainless steel water-cooled probe was positioned at the center of the exhaust duct and the gas sample was pulled through the probe, two chilled condensers, and a particulate filter. The gas sample was then pumped to the control room for analysis by the continuous monitoring instruments. A schematic of the continuous train is illustrated by Figure 2-6.

2.5.2 Solid Samples

Solid samples were taken from the furnace in order to determine the percent burnout of the coal char. A standard Pyrex probe was used for collecting these samples. A glass cyclone was used for separation of particulates from the gas stream. A schematic of the solids sampling system is shown in Figure 2-7.

2.5.3 Gas Temperature Measurement

Gas temperatures were measured with a B-type thermocouple in a suction pyrometer jacket as shown in Figure 2-8. The pyrometer was placed in the flue gas steam with the opening in the ceramic sheath pointing downstream. A sufficient gas sample was drawn around the thermocouple tip such that the convective heat transfer from the gas to the thermocouple dominated over the radiation heat loss of the thermocouple tip to the surroundings.

2.6 Data Acquisition

Data for the Reburning Tower facility were obtained with the use of a continuous on-line computer and real-time data acquisition program. The program obtained input data every 35 seconds from each of the continuous gas monitors and from the pressure transducers and K-type thermocouples on each of the five laminar flow elements. With this information, the computer calculated firing rates, various stoichiometries, air and flue gas flow rates, and gas species concentrations on a zero percent O_2 basis. Information was displayed on the computer screen and a printer, if desired, to set up a particular experiment or change input variables.

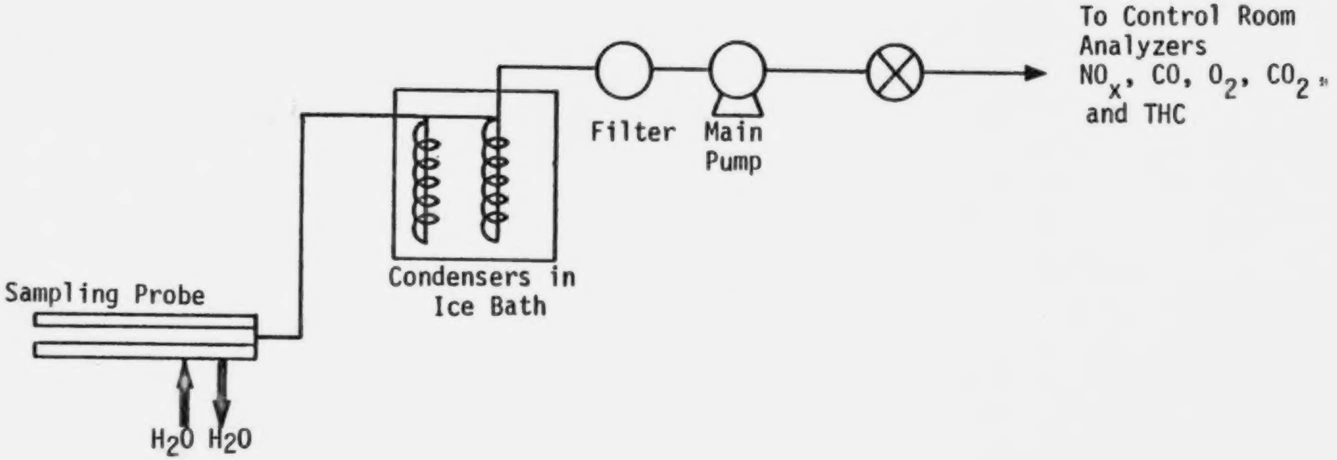

Sampling Probe
H_2O H_2O
Condensers in Ice Bath
Filter
Main Pump
To Control Room Analyzers
NO_x, CO, O_2, CO_2, and THC

Figure 2-6. Continuous monitoring sample system.

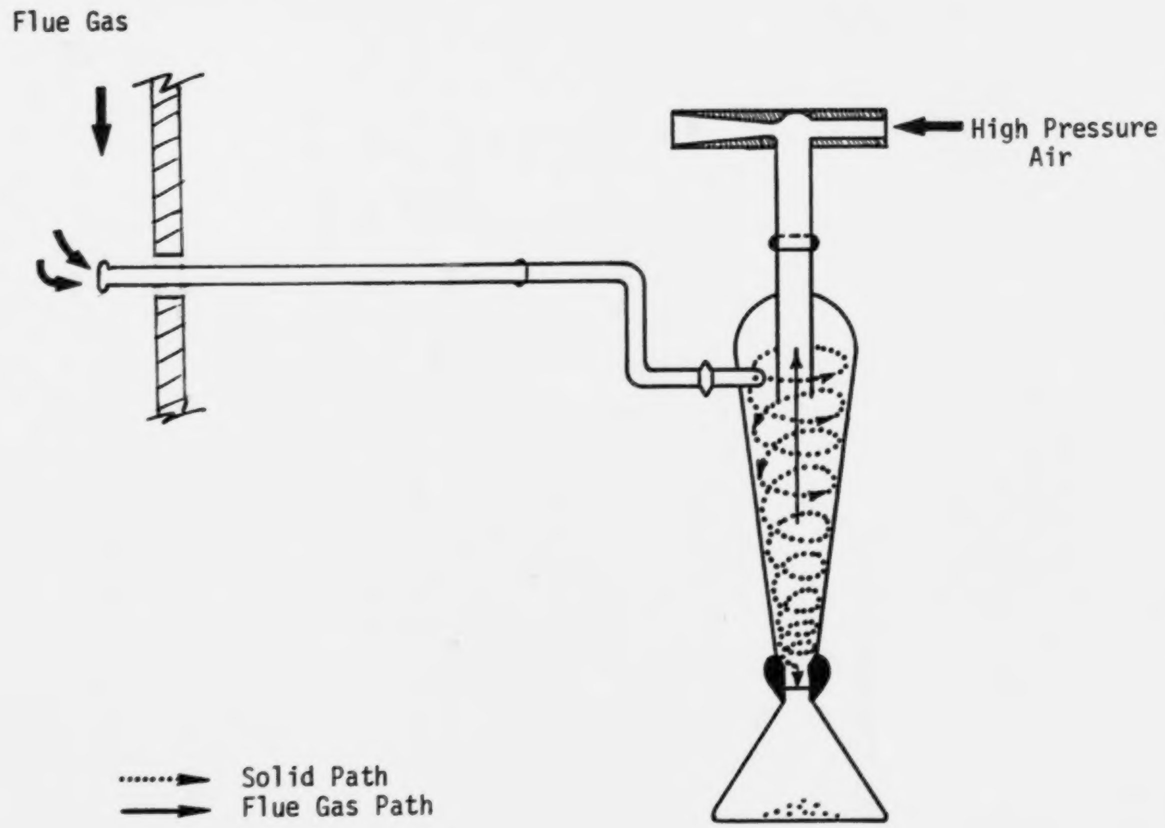

Flue Gas
High Pressure Air
Solid Path
Flue Gas Path

Figure 2-7. Solids sampling system.

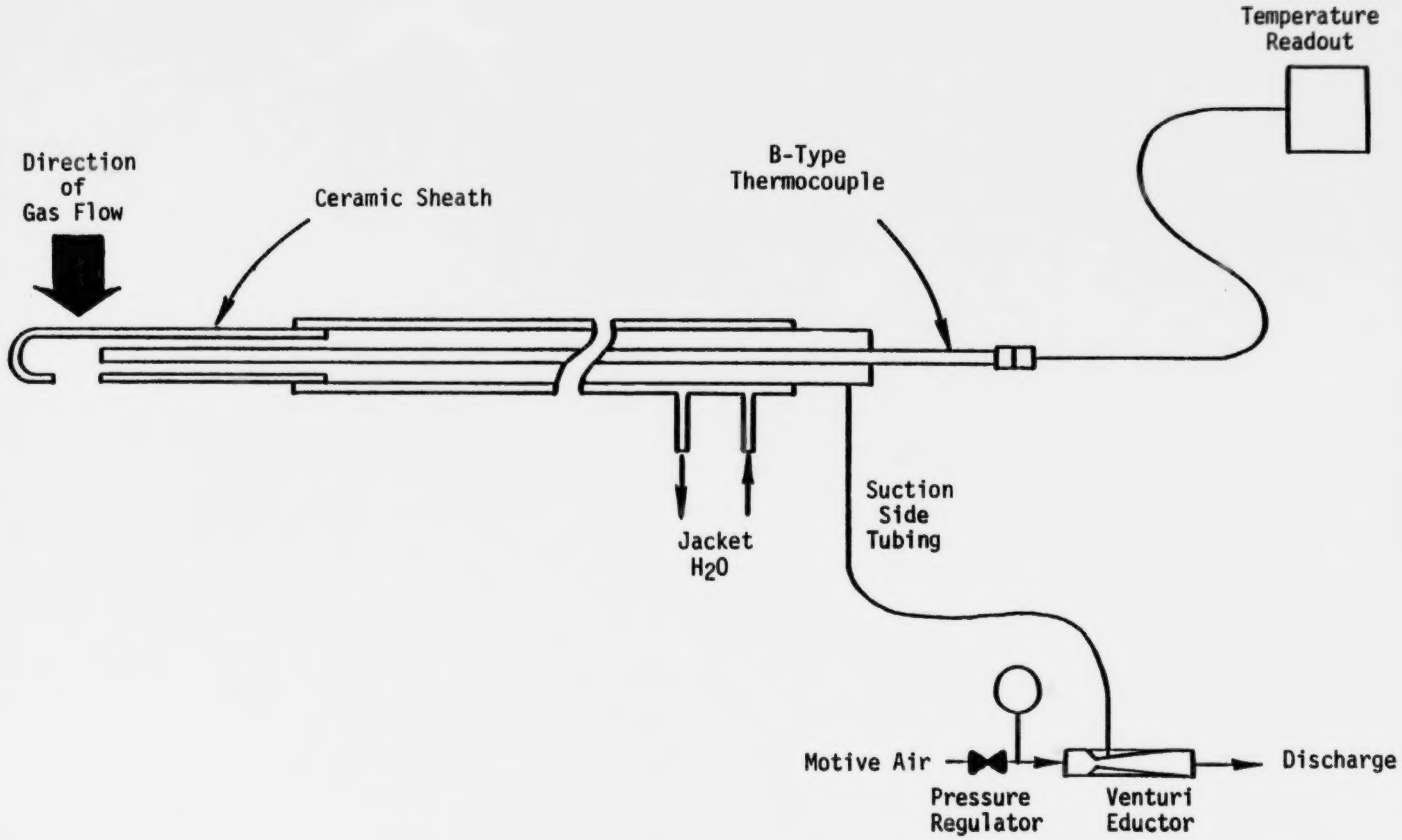

Direction
of
Gas Flow
Ceramic Sheath
B-Type
Thermocouple
Temperature
Readout
Jacket
H_2O
Suction
Side
Tubing
Motive Air
Pressure
Regulator
Venturi
Eductor
Discharge

Figure 2-8. Gas temperature measurement system.

3.0 FURNACE CHARACTERIZATION

The initial tests on the tower were performed in order to characterize the temperature, primary zone exit conditions, and NO_x emissions typical of the system. The majority of the tests in the program used Utah coal as fuel, with natural gas occasionally employed as an alternative fuel. Indiana coal was employed for sorbent studies due to its high sulfur content. The solid fuels were prepared for use by pulverization to an average size of 70 weight percent passing 200 mesh screen. Analyses of the fuels are listed in Table 3-1.

3.1 Thermal History Characterization

A fundamental design consideration for the reburning tower was the ability to duplicate typical temperature histories of existing utility boilers. Thus, the initial tests performed on the Reburning Tower involved the characterization of the thermal history of the furnace. A temperature profile at 10 MBtu/hr of Utah coal was obtained, and from this information it was decided that more cooling was required on the lower end of the furnace in order to achieve the desired quench rate. Six cooling panels were installed, two at level six and four at level 7, and the temperature profile was repeated. Figure 3-1 illustrates this profile and compares it with several real boiler profiles. The Reburning Tower had a fairly high quench rate and falls in the middle of the boiler profiles. Figure 3-2 shows that between 2250 and 2000°F the tower had a quench rate of about 360°F/sec, and if the temperature range was extended down to 1700°F, the quench rate increased to nearly 500°F/sec.

3.2 Uncontrolled Emissions

After characterization of the thermal history of the furnace, tests were run at several different primary firing rates to determine the uncontrolled NO_x emissions. Excess air curves were run for loads of 9.5, 8.5 and 7.5 MBtu/hr with the resulting emissions shown in Figure 3-3. Uncontrolled NO_x emissions were found to increase with excess air and emissions were

TABLE 3-1. FUEL ANALYSES

Property / Fuel	Utah Coal	Indiana Coal	Natural Gas
Rank	HVB	HVB	-
Proximate Analysis (wt %, as received)			
Moisture	8.2	5.07	
Ash	8.64	9.34	
Volatile Matter	37.56	30.24	
Fixed Carbon	45.60	55.35	
Calorific Value (Btu/lb)	13031	12,545	21,088
Ultimate Analysis (wt %, dry)			2.28% CO_2
C	72.60	72.16	72.15
H	5.47	4.71	23.04
N	1.17	1.32	1.94
S	0.69	1.06	0
Ash	9.41	9.84	0
O	10.66	10.91	0.59

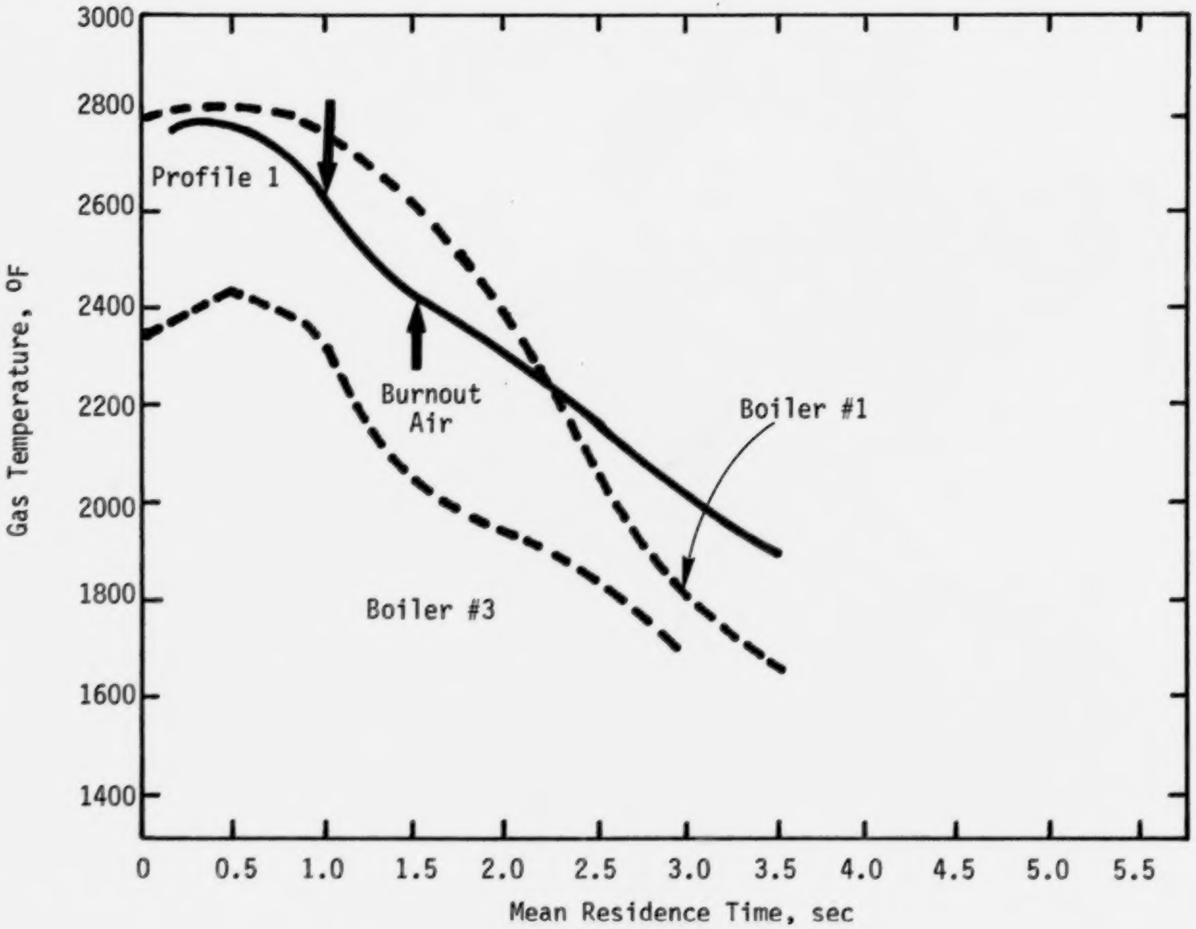


Figure 3-1. Reburning Tower temperature profile.

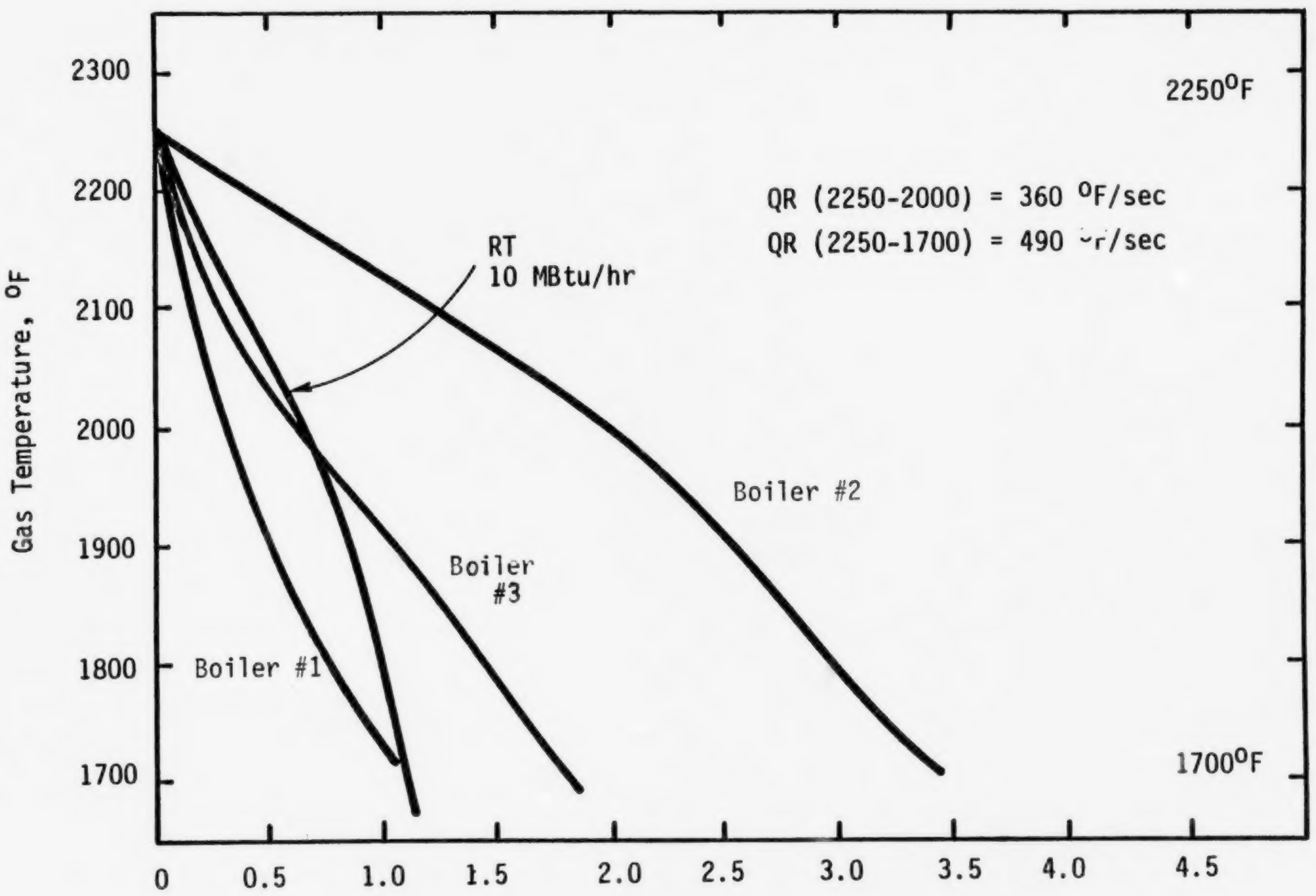


Figure 3-2. Quench rate comparison.

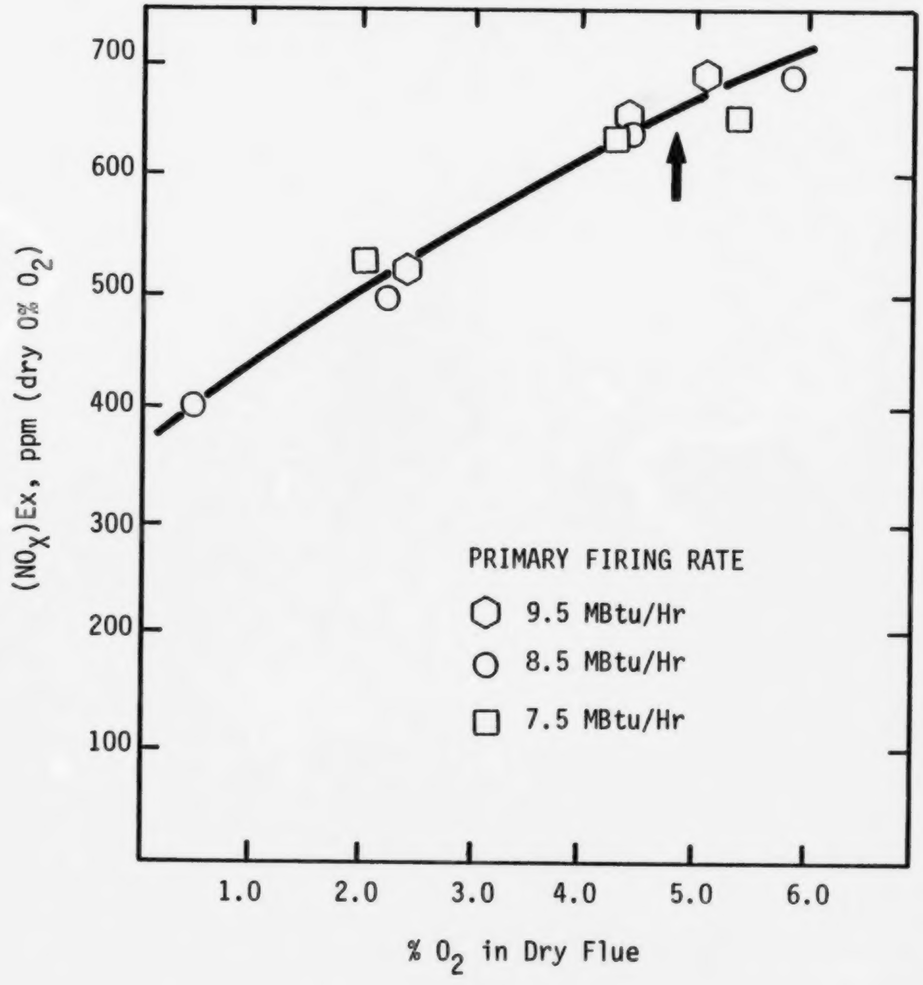


Figure 3-3. Reburning Tower uncontrolled NO_X emissions.

relatively insensitive to variations in load. The arrow at approximately 5.0% O_2 represents the overall stoichiometry used during the reburning study. Percent NO_x reduction can be determined from the NO_x level when reburning was applied relative to the uncontrolled NO_x emissions at the same overall stoichiometry. At the conclusion of these characterization studies, reburning conditions were applied.

4.0 IMPACTS OF PROCESS PARAMETERS

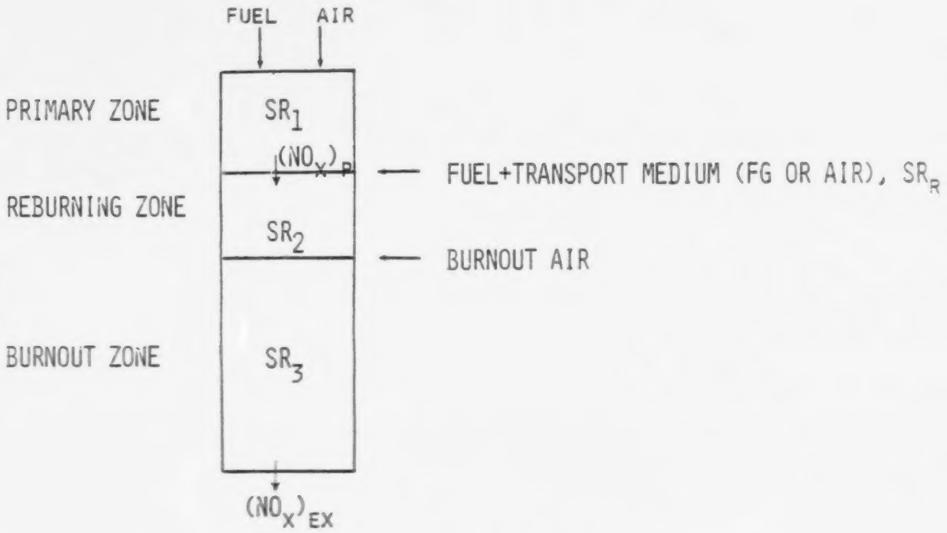
The experimental approach to the reburning process is outlined in Figure 5-1. Conceptually, the process can be divided into three zones: a fuel-lean primary zone in which the majority of the total fuel is burned, a fuel-rich secondary or reburning zone, and a final tertiary or burnout zone operated at fuel-lean conditions. The characteristic stoichiometries of the primary, reburning, and burnout zones are referred to a SR_1, SR_2, and SR_3, respectively.

The baseline operating conditions and location of injectors used throughout the testing program are given in Figure 4-2 unless otherwise noted. The total load of the furnace (primary plus reburning load) was kept constant at 10 MBtu/hr with the baseline case of 8.5 MBtu/hr Utah coal fired in the primary zone. The baseline configuration for the reburning zone specified four 2.8 in. ID jets on one wall of the furnace which fired 1.5 MBtu/hr Utah coal with a transport medium of 10 percent flue gas recirculation. The reburning injectors were located 10.5 ft from the main burner face at which point the bulk gas temperature was about $2550^{o}F$. For most of the experiments, the burnout air was injected into the furnace at 16.0 ft downstream through four 5.8 in. ID jets, also located on one wall of the furnace. The overall stoichiometry (SR_T) was held constant at 1.3 thus, the burnout air flowrate varied inversely with the primary air flowrate to maintain a constant overall air flow. All of the baseline conditions were chosen based on earlier work at EER on the CTT and on the initial pilot scale test results.

The process variables investigated in the parametric studies were grouped into three categories: primary zone, reburning zone and burnout zone parameters. The specific variable addressed in these categories were as follows:

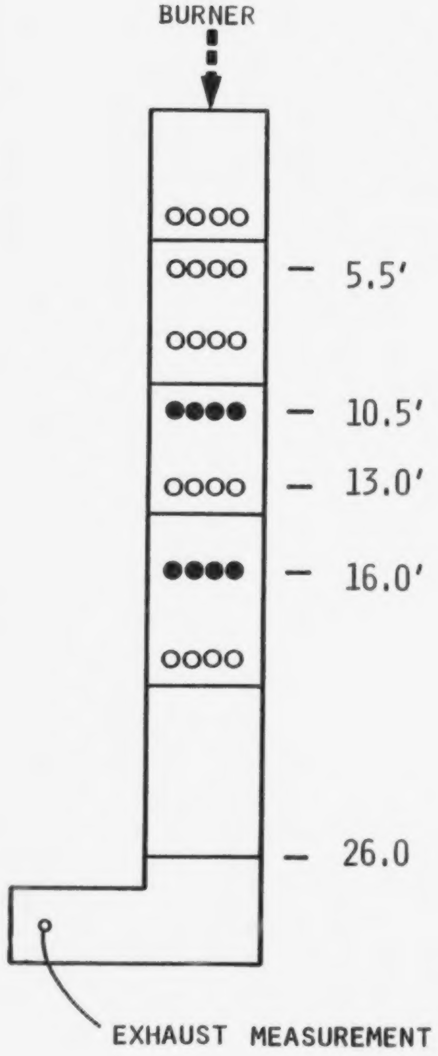
Primary Zone

- Stoichiometry, (SR_1)


FUEL
AIR
PRIMARY ZONE
SR_1
$(NO_x)_P$
FUEL+TRANSPORT MEDIUM (FG OR AIR), SR_R
REBURNING ZONE
SR_2
BURNOUT AIR
BURNOUT ZONE
SR_3
$(NO_x)_{EX}$

- CONSTANT LOAD (10 MBTU/HR)
- CONSTANT FUEL RATIO (5, 15, OR 25% REBURNING FUEL)
- CONSTANT SR_3

Figure 4-1. Experimental approach to reburning process.


BURNER
OOOO
OOOO
OOOO
●●●●
OOOO
●●●●
OOOO
— 5.5′
— 10.5′
— 13.0′
— 16.0′
— 26.0
EXHAUST MEASUREMENT

- BASELINE CONDITIONS

10 MBTU/HR TOTAL LOAD WITH UTAH COAL
- 8.5 MBTU/HR PRIMARY LOAD
- 1.5 MBTU/HR REBURNING LOAD

REBURNING FUEL INJECTION AT 10.5′
- FOUR 2.8″ ID REBURNING JETS (1 WALL)
- 10% FGR TRANSPORT FOR REBURNING COAL

BURNOUT AIR INJECTION AT 16.0′
- FOUR 5.8″ ID AIR JETS (1 WALL)
- $SR_3 = 1.3$

Figure 4-2. Baseline conditions for the reburning process.

- Primary NO_x concentration, $(NO_x)_p$

Reburning Zone

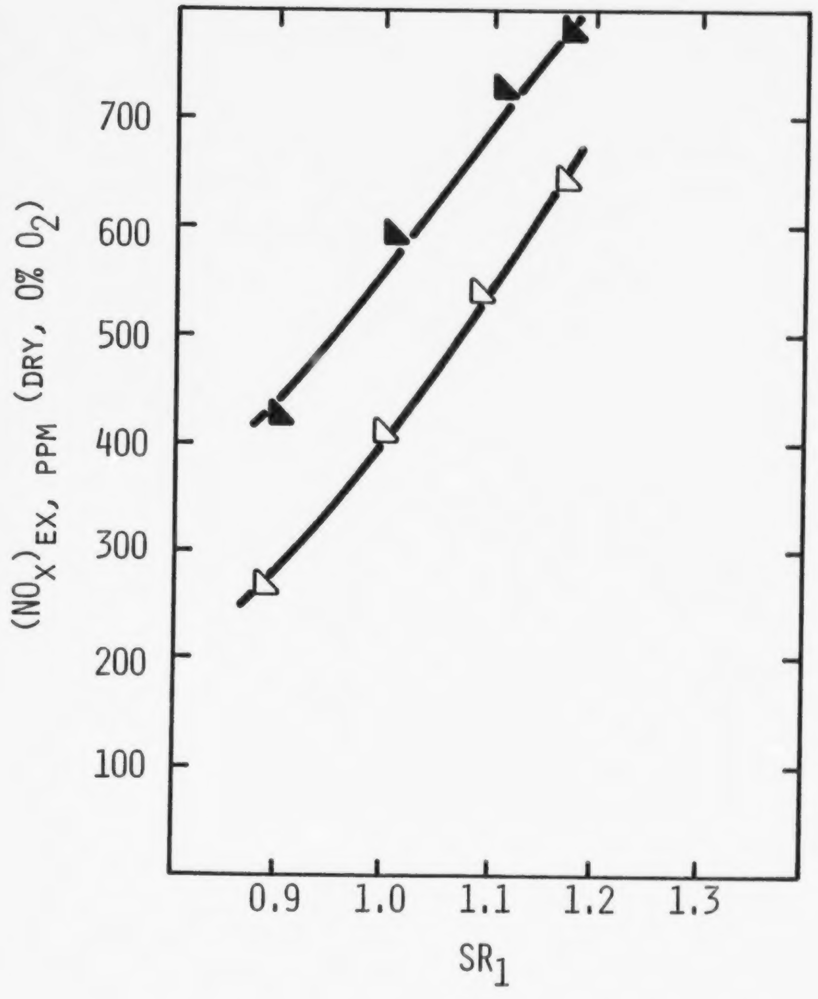
- Stoichiometry, (SR_2)
- Reburning fuel ratio
- Reburning fuel transport medium oxygen content, (SR_r)
- Residence time, (T_2)
- Thermal history
- Injection location
- Reburning fuel type

Burnout Zone

- Overall stoichiometry (SR_3)

4.1 Reburning Fuel Transport Line Stoichiometry

The ratio of the oxygen present in the reburning fuel transport line to the theoretical oxygen required for complete combustion of the reburning fuel is refered to as the reburning transport stoichiometry, SR_r on the reburning process are shown in Figure 4-3. The experiments were performed as outlined in the previous section, with equivalent volumetric flow rates of FGR or air employed as the reburning fuel transport medium. The figure shows that a change in SR_r had a significant effect on NO_x emissions. With SR_1 varied from 0.9 to 1.2, a 40 to 20 percent decrease in NO_x emissions resulted when SR_r was decreased from 1.01 to 0.40. The premixing of the reburning fuel with the substantive amounts of O_2 which were present in the transport line when SR_r was increased resulted in the NO_x increase. The rise in NO_x transport line when SR_r was increased resulted in the NO_x increase. The rise in NO_x emissions was characteristic of systems which utilize premixed burners. The formation of NO_x from fuel nitrogen increased due to the availability of oxygen in locally fuel-lean "pockets", and thermal NO_x formation was enhanced by the elevated flame temperature common to premixed burners.



SR_1	SR_2	
	FGR $(SR)_r = .40$	AIR $(SR_r) = 1.01$
0.90	0.82	0.92
1.00	0.91	1.00
1.10	0.99	1.09
1.17	1.05	1.15

Figure 4-3. Influence of reburning transport stoichiometry on NO_X emissions.

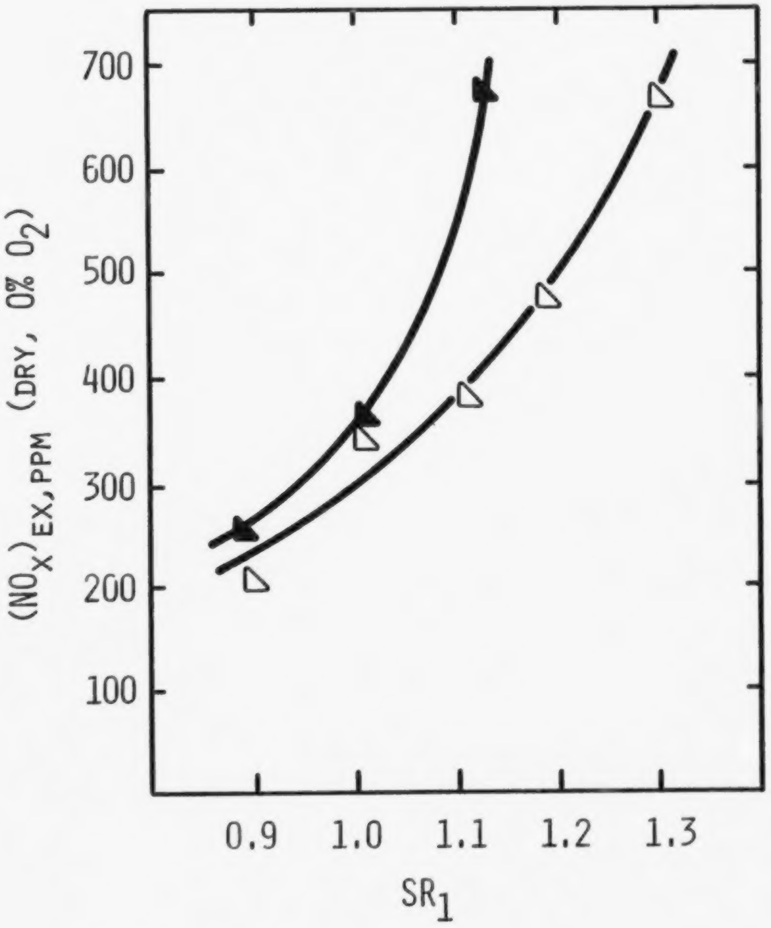
Whereas 15 percent reburning fuel was used for the data shown in Figure 4-3, the results shown in Figure 4-4 were obtained when 25% reburning fuel was used for a similar experiment. This figure shows that the influence of the transport medium on NO_x emissions becomes less important as the reburning zone the more fuel rich. As the reburning zone stoichiometry decreases, the influence of premixing the reburning fuel with oxygen becomes secondary to the effect of the extremely fuel rich environment in the reburning zone, and the values of NO_x emissions converge. The fuel lean "pockets" which previously existed were dissipated due to the overall lack of oxygen in the reburning zone.

This result is complementary to the results obtained on the bench scale CTT, illustrated in Figure 4-5. The bench scale tests were run by altering the flow rate of reburning fuel while holding all primary zone parameters plus the flow rate of the reburning carrier gas constant. Similar to the pilot scale results, the data for the bench scale facility converged as the reburning zone became more fuel rich.

To obtain a reburning zone stoichiometry low enough to minimize the effect of the transport medium, a large percentage of the total load must be injected as reburning fuel. For the pilot scale tests performed, it was necessary to run the primary zone fuel-rich to obtain a reburning zone stoichiometry this low. When this was the case, it was, in effect, multiple staged combustion rather than reburning. Hence, for the range of reburning loads and primary zone stoichiometries desired in an actual furnace, a transport medium as inert as possible yields optimal results.

4.2 Primary Zone Stoichiometry

Data obtained form experiments which investigated the influence of primary zone stoichiometry on the reburning process are illustrated in Figure 4-6. The experiment was performed such that the total volumetric flow rate of primary effluent was held constant for all SR_1 values tested. This was accomplished by varying the reburning load while holding the total load constant. With the experiment performed in this manner, SR_1 could be varied



SR_1	SR_2	
	FGR $(SR)_r$=.13	AIR (SR_r)=.52
0.90	0.71	0.81
1.00	0.78	0.88
1.10	0.86	0.96
1.20	0.93	1.03

Figure 4-4. SR_r effect on NO_X emissions at low reburning zone stoichiometries.

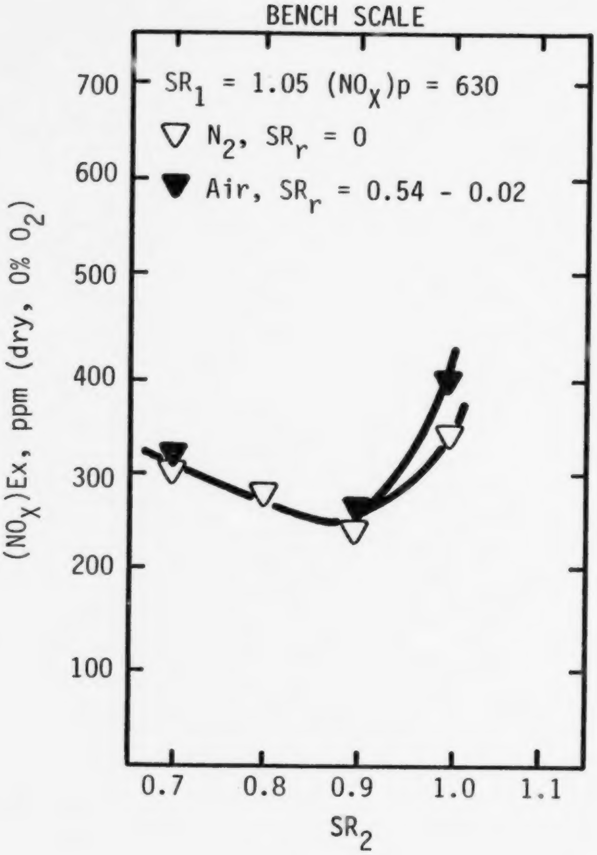


Figure 4-5. Transport medium effect for bench scale facility.

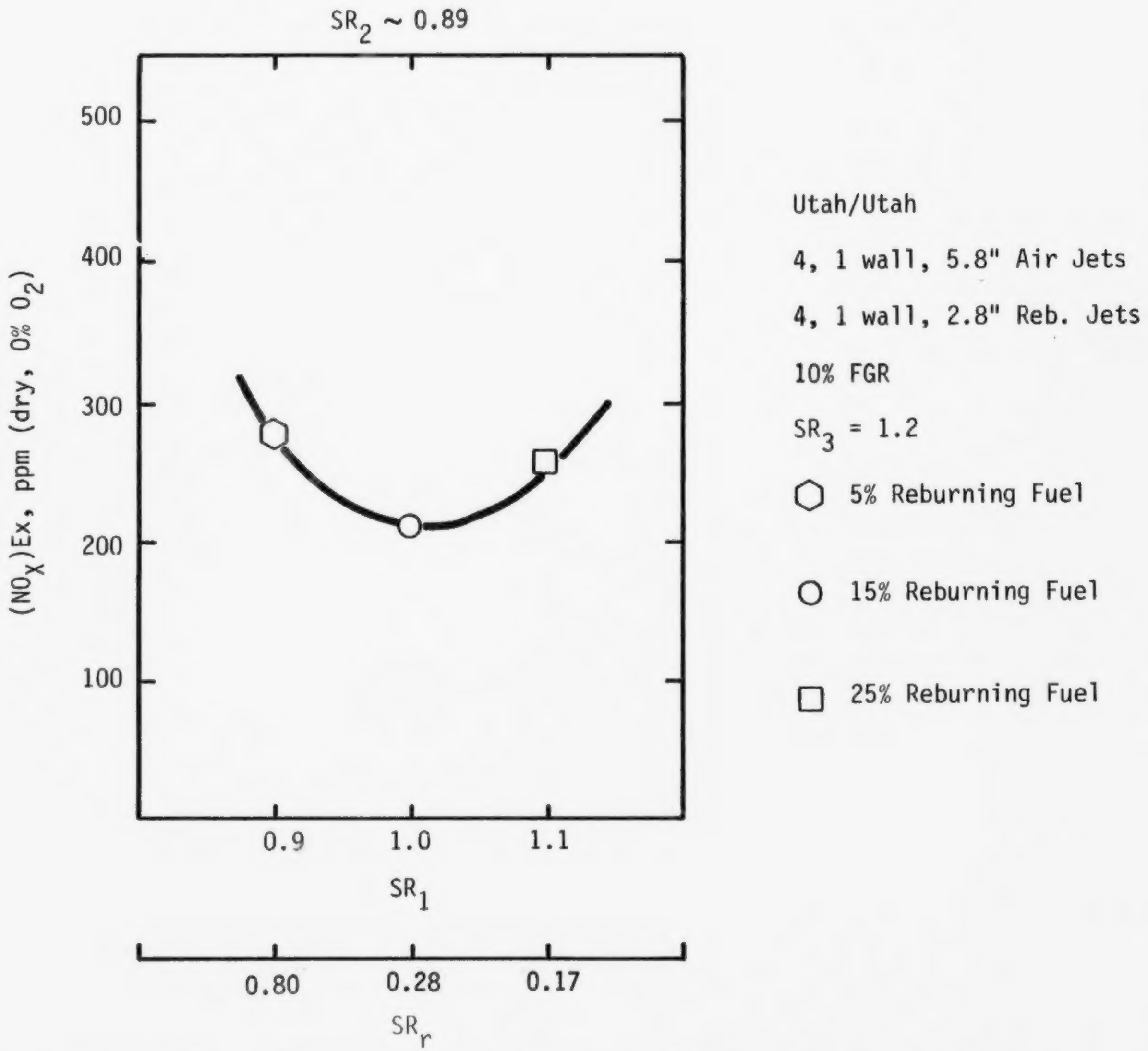


Figure 4-6. Influence of primary zone stoichiometry on NO_x emissions.

without a change in the reburning zone residence time. The data in Figure 4-6 indicates that the primary zone stoichiometry does have an effect on exhaust emissions. A minimum was present at an SR_1 of one, but since the tests were performed at a constant FGR flow rate to negate the influence of mixing, an SR_r effect was coupled to this data. Based on the results discussed in Section 4.1, comparison of the data at a common SR_r of 0.28 would result in a decrease in NO_x emissions of about 40% at the point where SR_1 was 0.9. This would shift the point down such that the curve has a positive slope throughout.

Results form the bench scale facility are shown in Figure 4-7. For these tests, an inert reburning fuel transport medium was employed, so no SR_r\ effect was present. As with the pilot scale tests, results indicated that the primary zone excess air level should be at the lowest point possible in order to minimize NO_x emissions.

4.3 Reburning Zone Stoichiometry

The influence of reburning zone stoichiometry, SR_2, on the reburning process is presented in Figure 4-8. Experiments were performed in a manner similar to the SR_1 tests. With total load and SR_1 held constant, the primary air flow rates were varied to accommodate the change in primary load which accompanied a change in reburning load. Hence, reburning zone residence times were different for each point, but only a minimal effect on NO_x emissions was expected since the difference was small.

Figure 4-8 shows that an optimum reburning zone stoichiometry exists. Although the effect of SR_r discussed in the previous sections would tend to alter the position of the data points in Figure 4-8, the change which would result if comparisons were made on a common SR_r basis would not be significant enough to alter the overall shape of the curve. (A minimum would still exist.) Once again, this conclusion is in agreement with bench scale results, as shown in Figure 4-9.

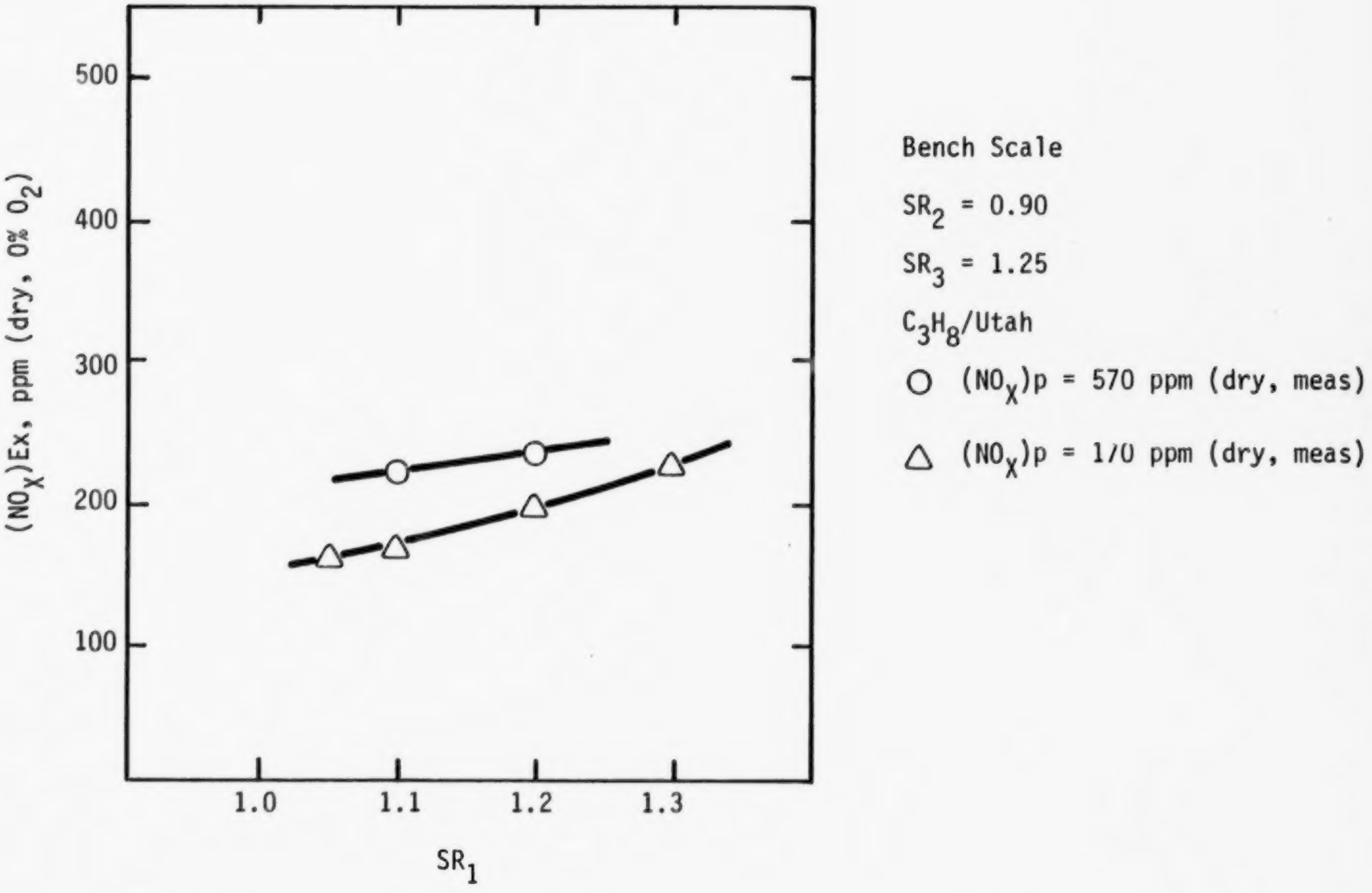


Figure 4-7. Primary zone stoichiometry effect for bench scale facility.

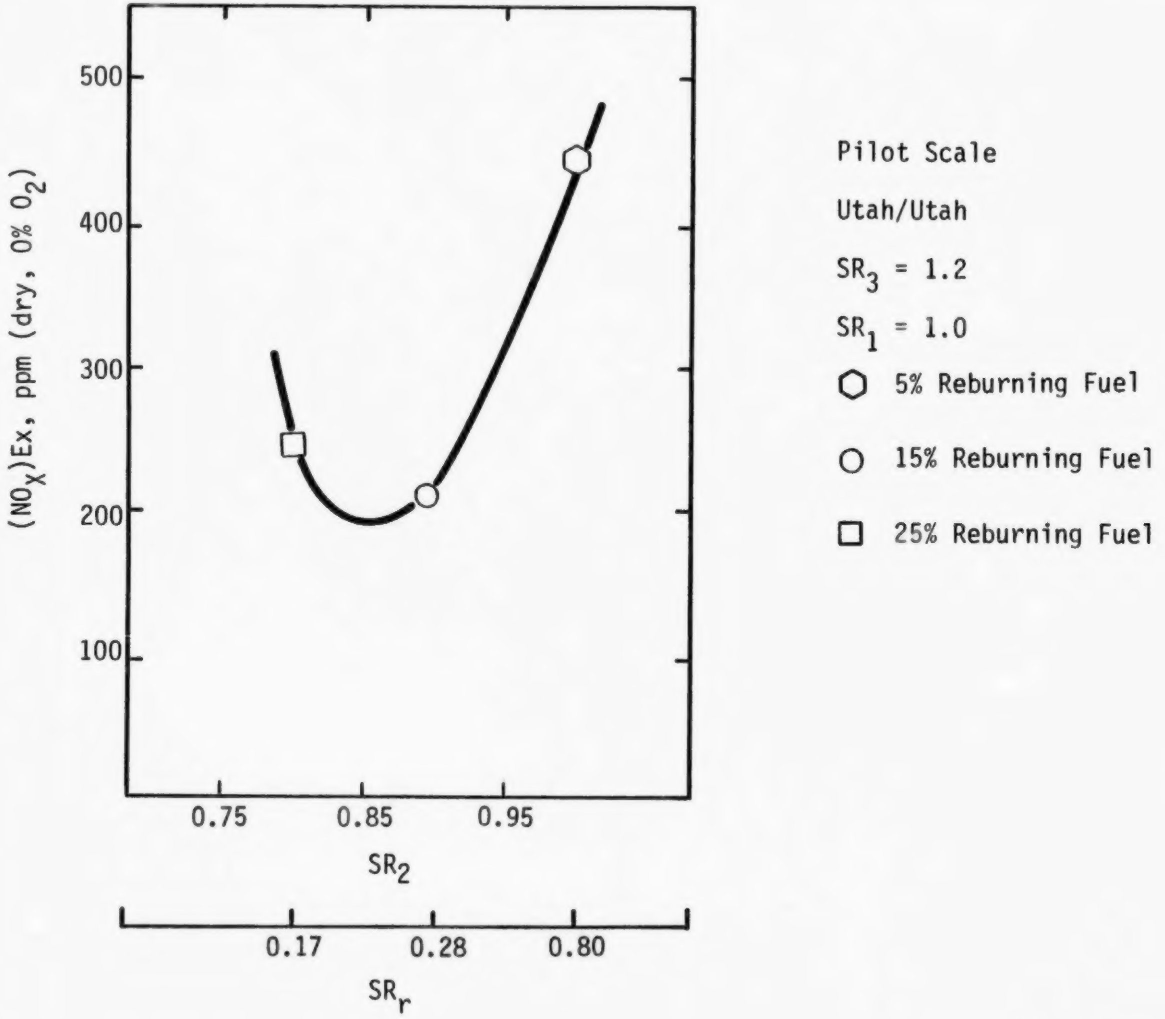


Figure 4-8. Influence of reburning zone stoichiometry on NO$_x$ emissions.

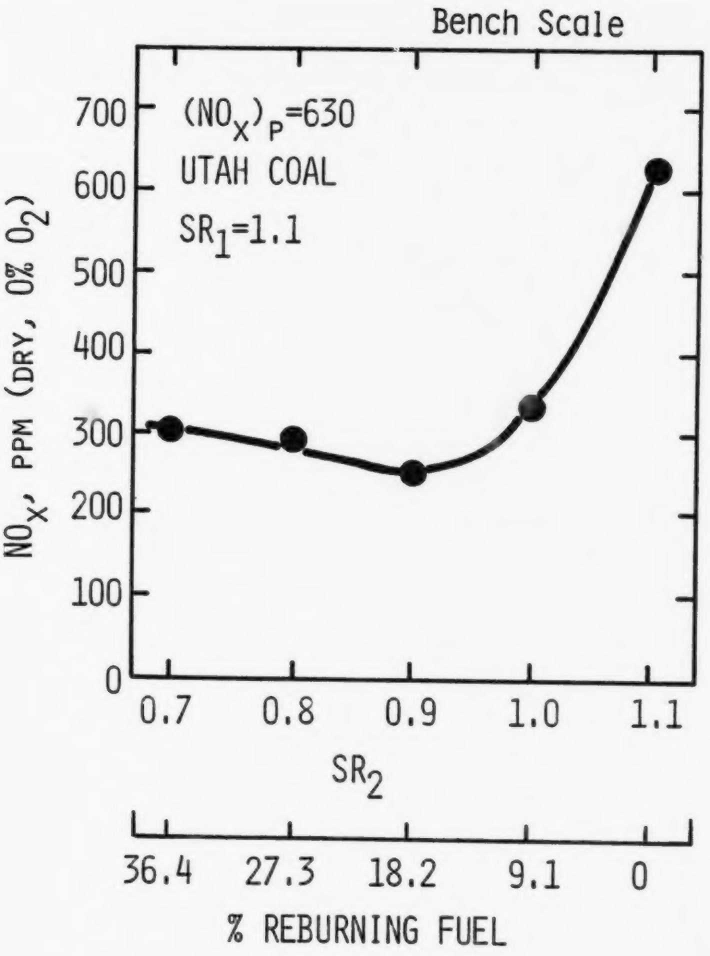


Figure 4-9. Reburning zone stoichiometry influence for bench scale facility.

Data represented in Figure 4-9 were obtained at constant SR_1 and SR_r. The minimum which occurred in these curves has been shown to be a result of changes in the XN speciation (Greene, et al, 1984). Specifically, a decrease in NO concentration that occurred as SR_2 decreased was accompanied by a increase in the concentration of other XN species which could be converted to NO in the burnout zone.

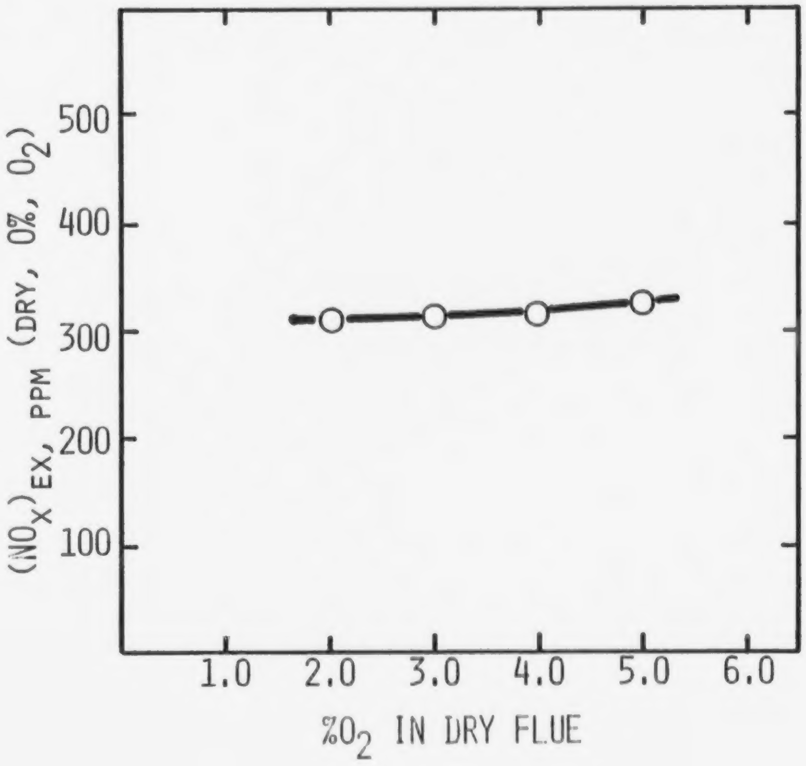
4.4 Burnout Zone Stoichiometry

The influence of burnout zone or overall stoichiometry, SR_3, on the reburning process is illustrated in Figure 4-10. No effects of SR_3 were noted which was generally in agreement with bench scale results, shown in Figure 4-11, as well as results obtained form previous reburning studies (Greene, et al, 1984).

5.5 Reburning Zone Residence Time

The influence of reburning zone residence time was investigated by physically moving the location at which burnout air was injected. By performing the experimental work in this manner, the primary zone exit temperature was held constant while the reburning zone exit temperature was decreased when residence time increased. Greene, et al (1984) found that the reburning zone exit temperature had no influence on the reburning process as long as thermal conditions were above the "de-NO_x" temperature window of about 1700°F. Results of the residence time experiments are presented in Figure 4-12. NO_x emissions decreased when residence time increased. This result was caused by the increased time that the NO species was allowed to decay in the reducing environment of the reburning zone.

Experiments performed on the CTT had similar results, shown in Figure 4-13. Further tests on this facility, which measured XN species exiting the reburning zone, showed that as residence time increased hydrocarbon reduction of NO in the reburning zone increased, thus restricting the amount of reactive nitrogen species available for conversion to NO in the burnout zone (Greene, et al, 1984).



ONE 8.8″ ID COAL JET

FGR = 350 ACFM

$SR_1 = 1.0$

FOUR 3.5″ ID AIR JETS

Figure 4-10. Influence of burnout zone stoichiometry on NO_X emissions.

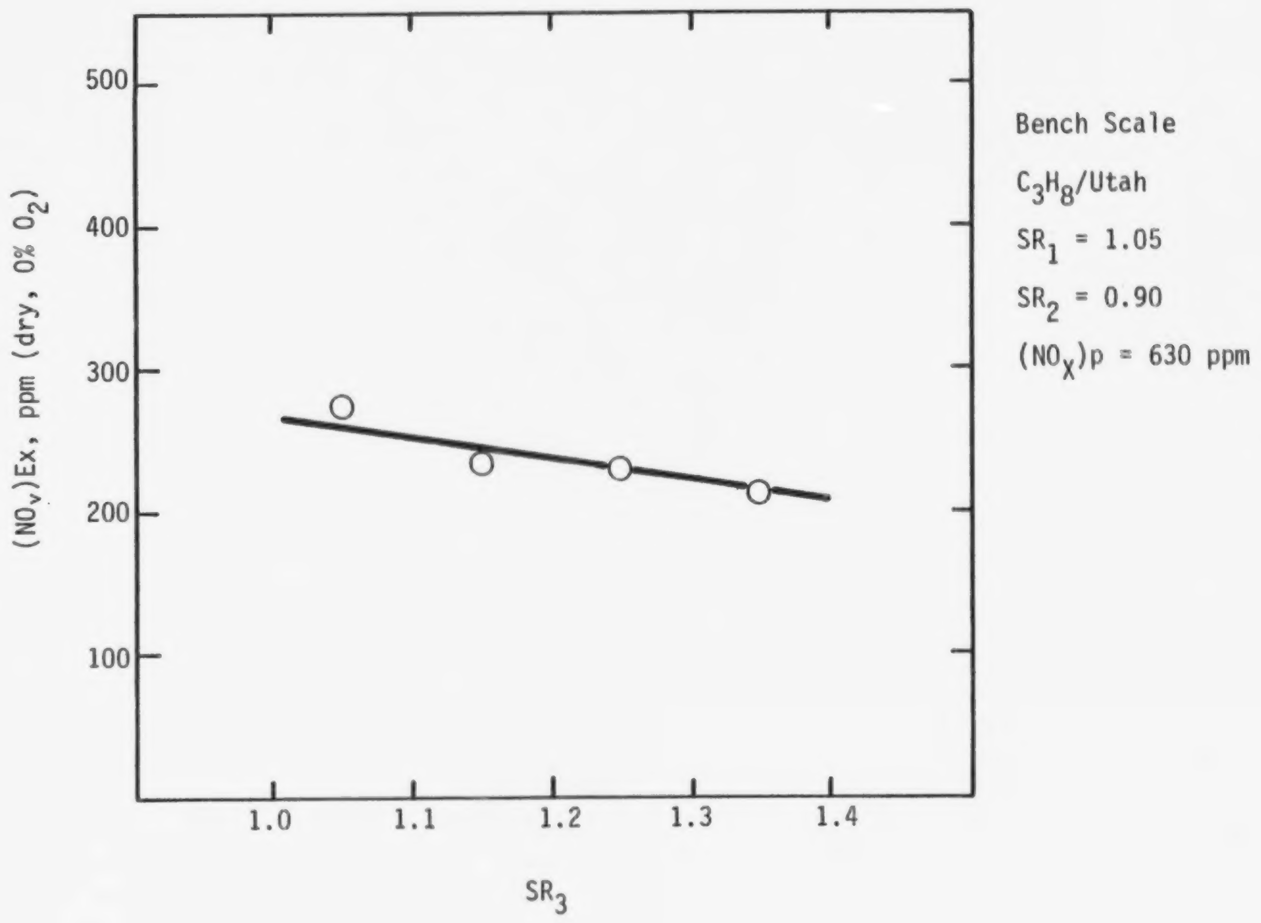


Figure 4-11. Burnout zone stoichiometry influence for bench scale facility.

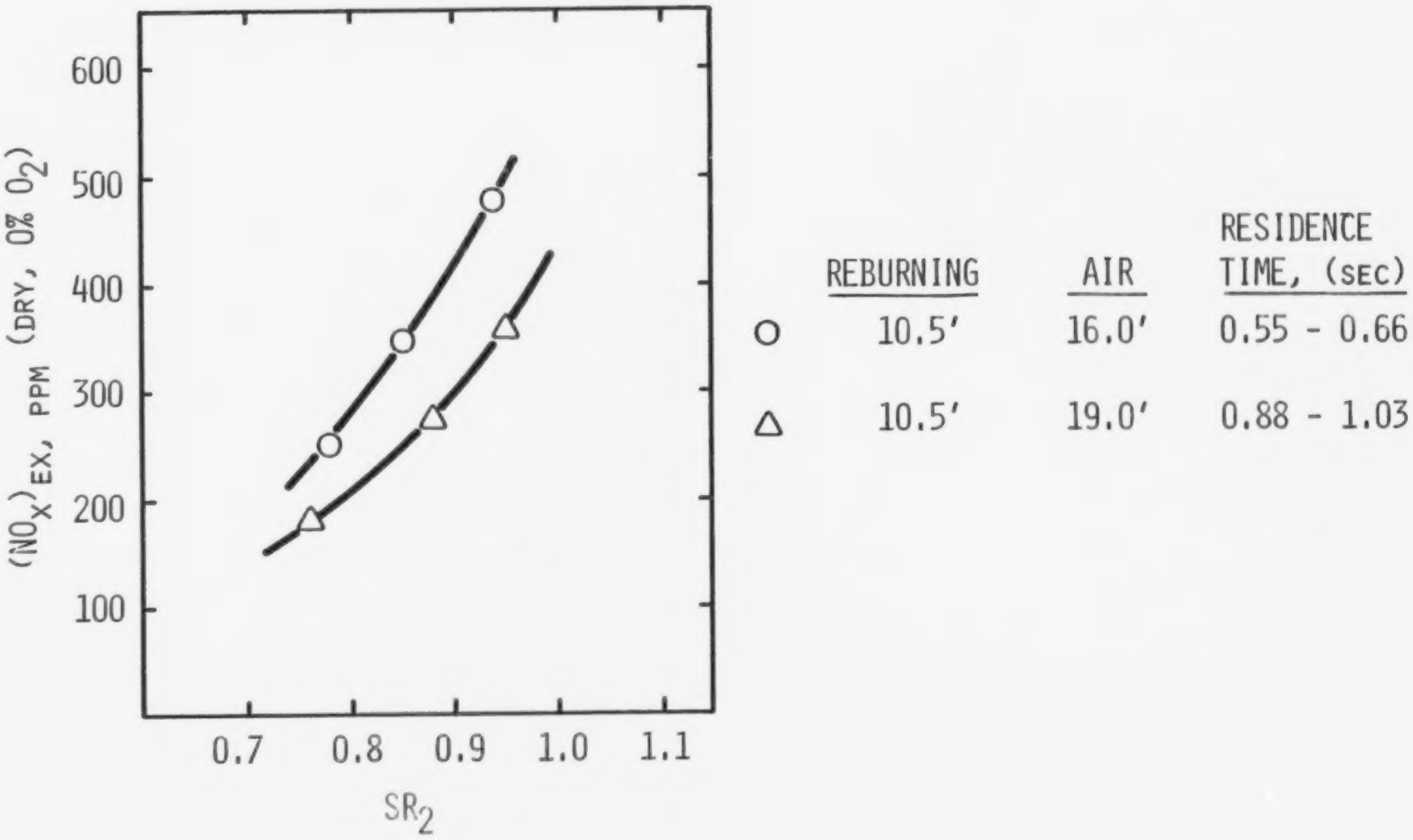


Figure 4-12. Influence of reburning zone residence time on NO_X emissions.

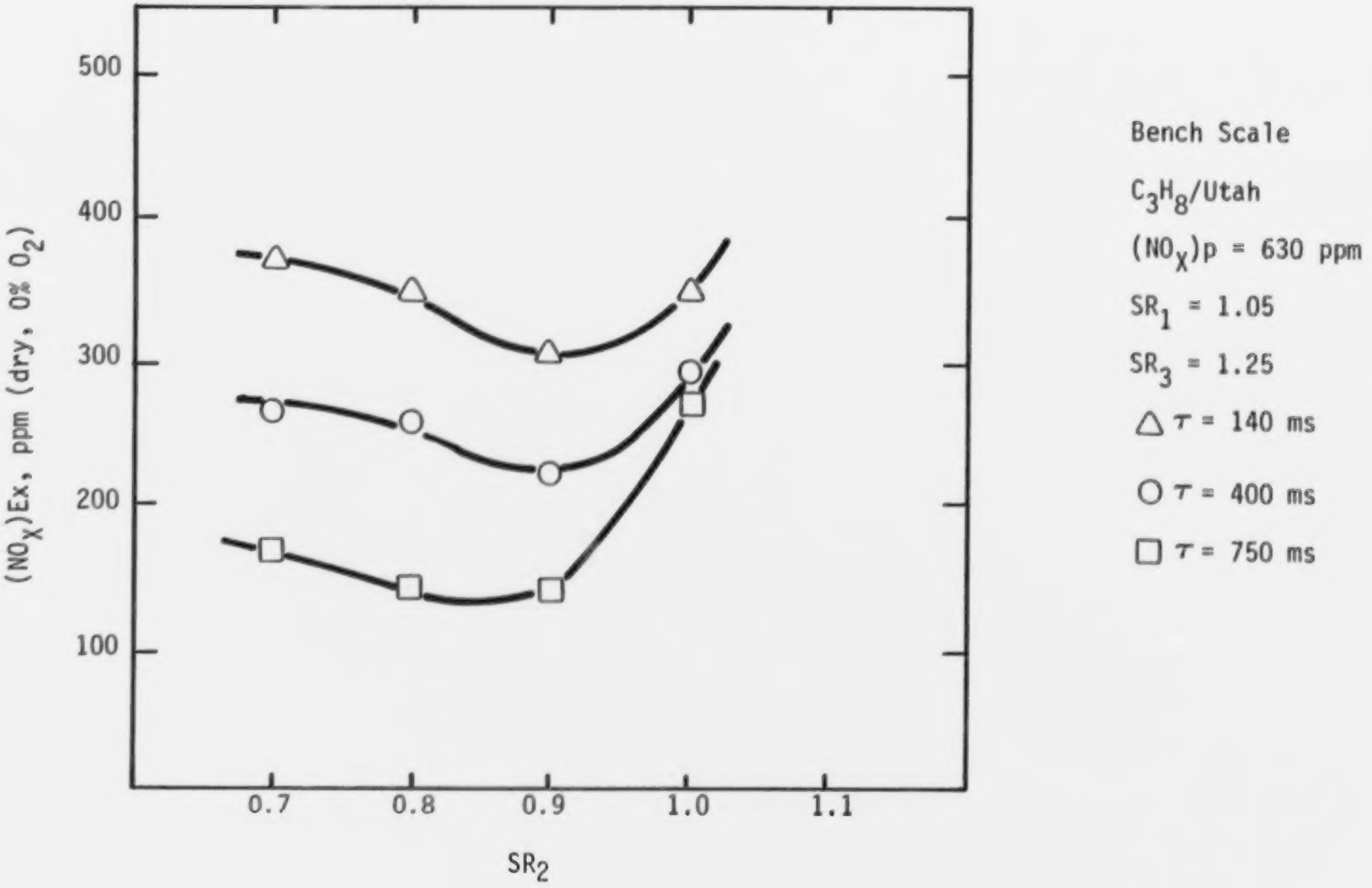


Figure 4-13. Reburning zone residence time influence for bench scale facility.

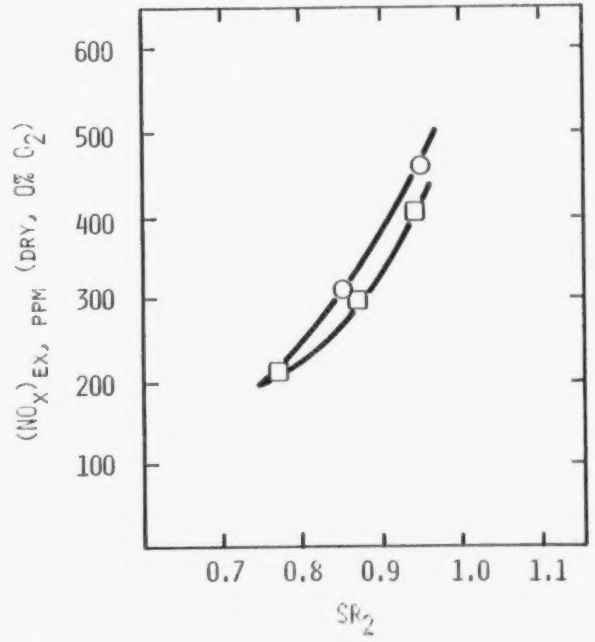
In terms of application to a full-scale boiler, the only real limitation to lengthening the reburning zone appears to be the point at which air must be injected to achieve complete carbon burnout before the gas reaches the boiler convective section. The air injection point is also likely to be dependent on the boiler design and fuel burning characteristics.

4.6 Reburning Fuel Injection Location

To explore the influence of reburning fuel injection location on the reburning process, the reburning injectors were moved two levels closer to the burner face (see Figure 4-2). This had an adverse effect on NO_x emissions, as shown in Figure 4-14. Difference in NO_x emissions between the two set of data were insignificant, even thought he reburning zone residence time was nearly doubled when the reburning fuel was injected closer to the burner face. The results indicate the necessity of a high degree of fuel burnout in the primary zone. With lower levels of primary burnout, unconsumed oxygen from the primary zone entered the reburning zone where it was available for oxidation of the reburning fuel, thus diminishing the reducing capability of the reburning zone. In practice, the reburning fuel injectors should be placed as close to the main burners as possible to gain high gas temperatures and long residence times, and yet, sufficient time must be given for the primary fuel to burn out.

4.7 Furnace Thermal History

After several weeks of experimental work on the Reburning Tower, it was noted that the temperature profile of the furnace had changed due to deposits of slag on the furnace walls. In Figure 4-15, the change in temperature profile is shown. Figure 4-16 illustrates the impact this change had on NO_x emissions. Although only a slight reduction in uncontrolled NO_x emissions occurred, the emissions which resulted when reburning was employed were substantially lower when the furnace was hotter. For profile 1, the reburning injection temperature was 2550°F with a primary oxygen of 3.6 percent while for profile 2, the injection temperature was about 2700°F with a primary oxygen at 2.3 percent. Theoretical oxygen is about 2.0 percent for



	REBURNING INJECTION	AIR	REBURN TIME (MSEC)	PRIMARY BURNOUT	PRIMARY UNBURNED O_2
○	10.5′	16.0′	0.55-0.66	~90%	3.6% (SR_1=1.1)
□	5.5′	16.0′	1.06-1.26	~80%	5.1% (SR_1=1.1)

Figure 4-14. Influence of reburning fuel injection location on NO_x emissions.

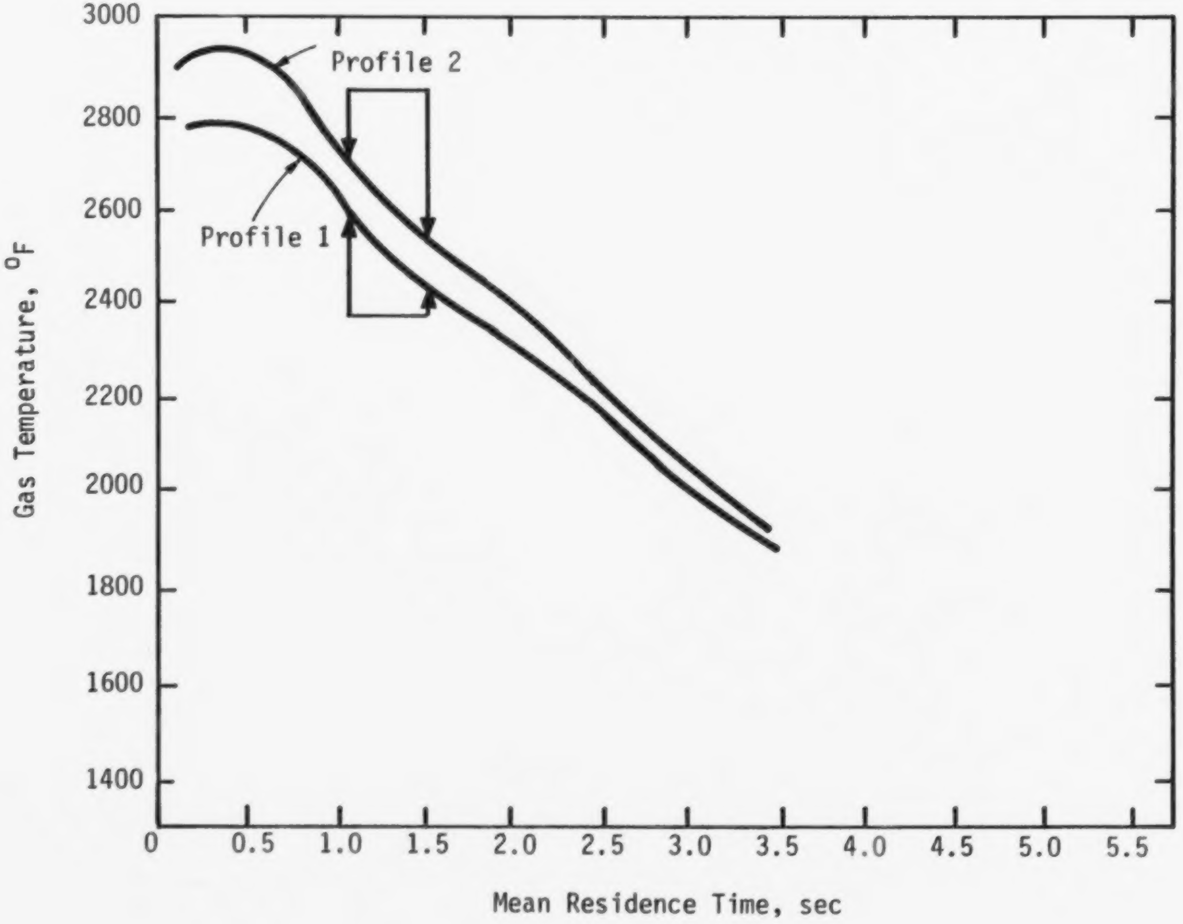


Figure 4-15. Comparison of reburning tower temperature profiles.

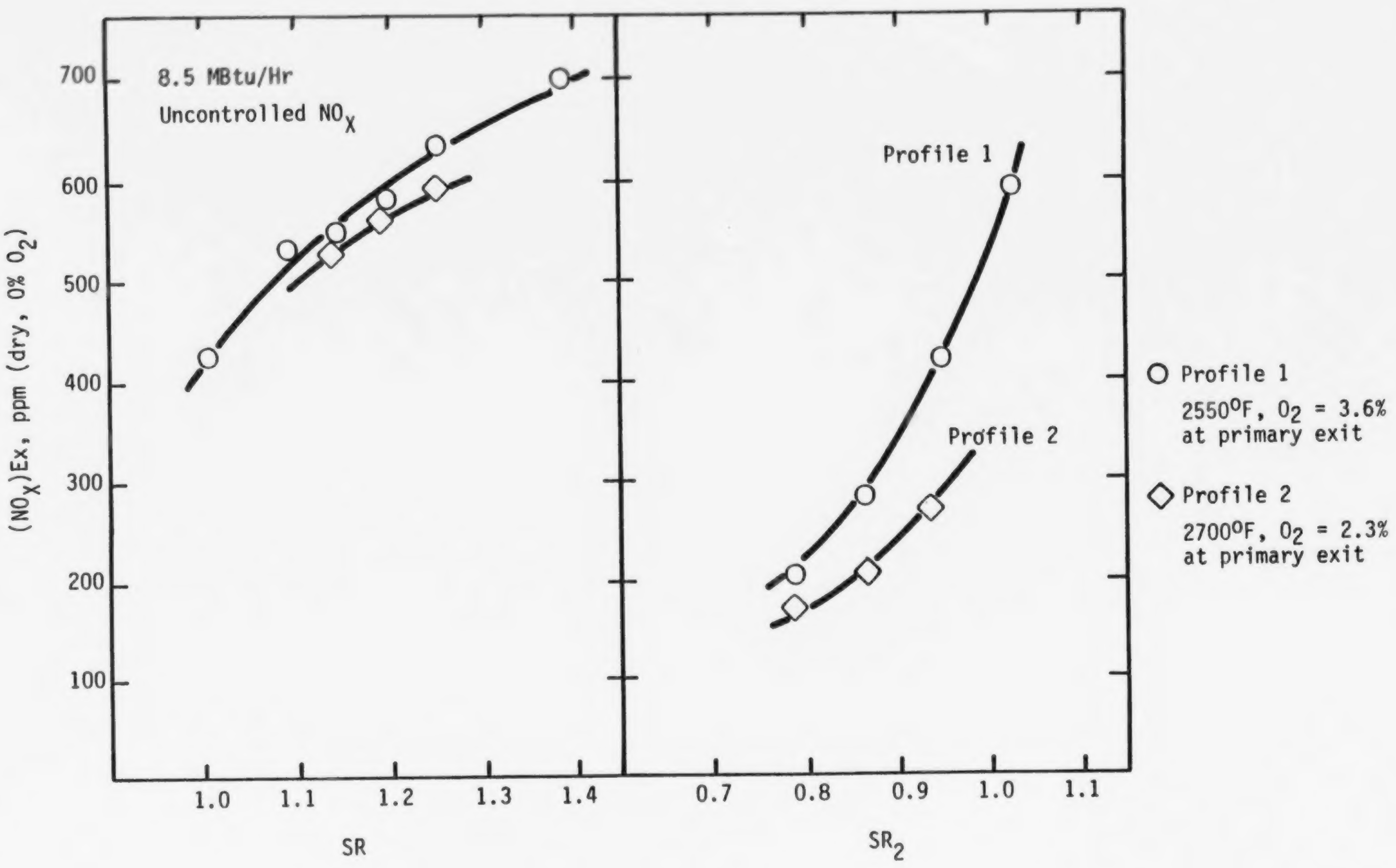


Figure 4-16. Influence of thermal history on NO_X emissions.

the Utah coal at an SR_1 of 1.1 which indicates that the colder profile had more unburned fuel and unused oxygen entering the reburning zone. The figure shows that the emissions were higher for the colder profile which can be attributed to the decreased reaction rates at lower temperature for the decay reaction and to the fact that the presence of additional oxygen leaving the primary zone effectively increased SR_2.

For experimental work on the CTT, the temperature profile was altered by increasing the primary load. The results are shown in Figure 4-17. Similar to the pilot scale tests,NO_x emissions decreased with an increase in furnace temperature. The effect was found to be more pronounced when the reburning fuel was free of fixed nitrogen.

4.8 Primary NO_x Concentration

Figure 4-18 compares results obtained when primary NO_x concentrations were extremely low, with those obtained when $(NO_x)_p$ reduction was most efficient. Although the difference in uncontrolled levels of NO_x emissions were substantial, the differences when reburning was employed were minor. Data from the CTT, shown in Figure 4-19, resulted in the same conclusion, where at high $(NO_x)_p$, the reduction was more efficient apparently due to the kinetic order of the reaction.

4.9 Reburning Fuel Ratio

Experimental work which investigated the influence of primary and reburning zone stoichiometries on the reburning process were performed by varying the amount of reburning fuel in order to obtain the desired stoichiometry. Results from these tests (see sections 4.2, 4.3) indicated that the excess primary air should minimized and that an optimal reburning zone stoichiometry existed. When the primary zone stoichiometry was constant, a unique percentage of reburning fuel resulted in the optimal reburning zone stoichiometry. Figure 4-20 illustrates the Reburning Tower results now plotted with percent reburning fuel on the abscissa. Figure 4-21 presents the CTT results. Both of these figures indicate that a reburning

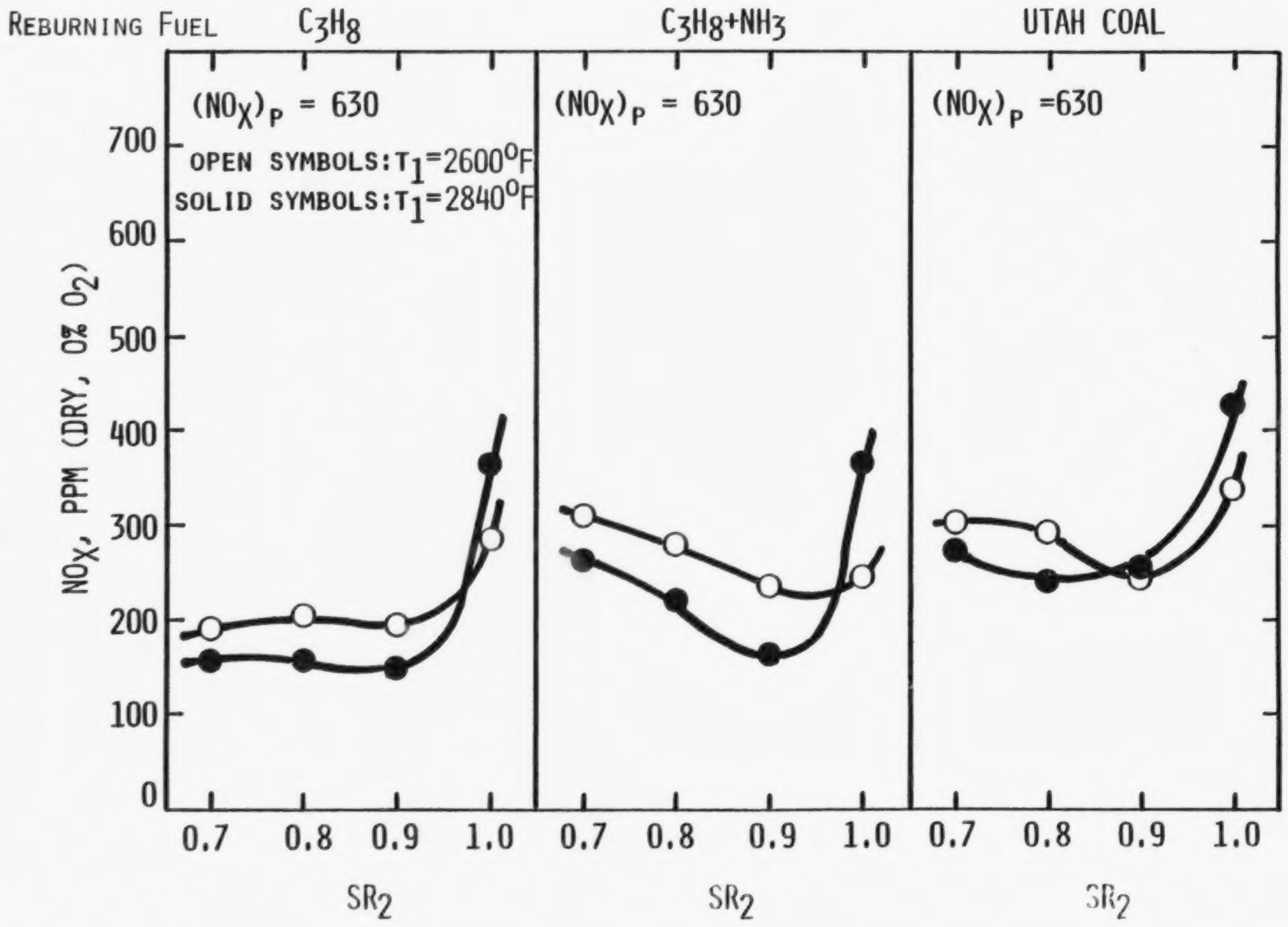


Figure 4-17. Furnace thermal history influence for bench scale facility.

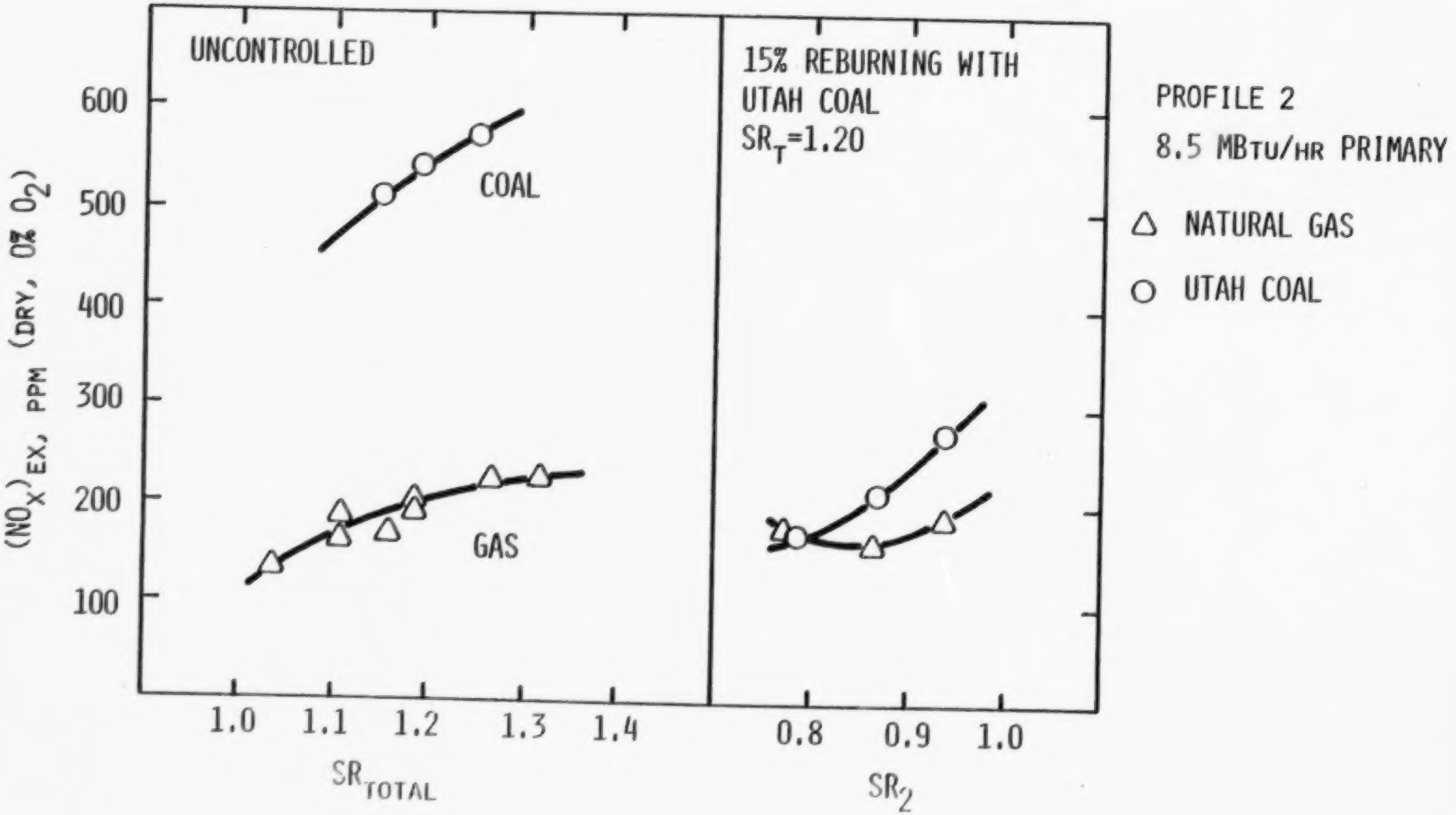


Figure 4-18. NO_x emissions for maximum and minimum reburning efficiency.

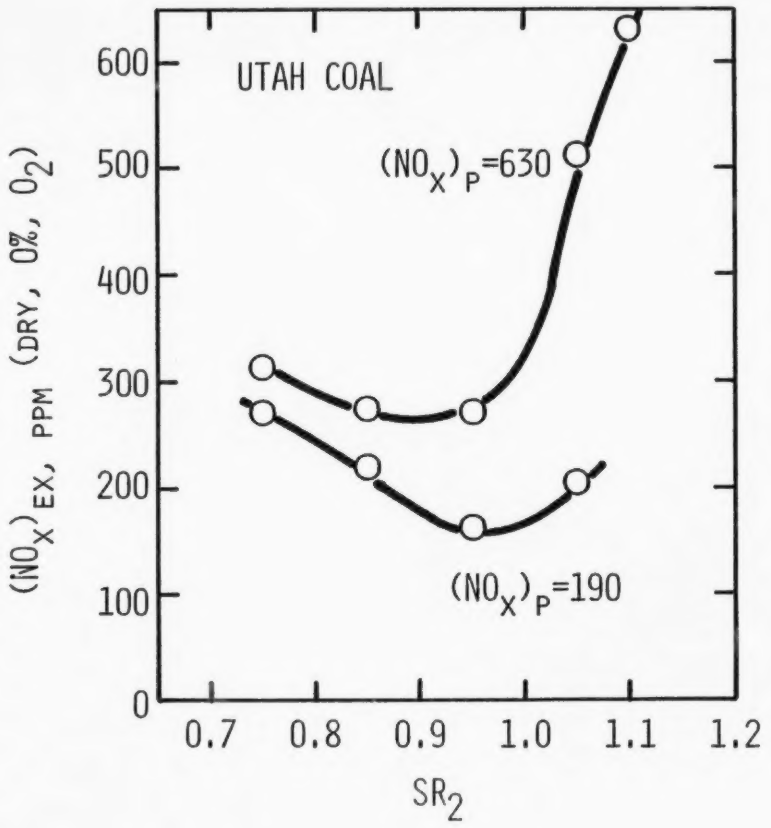
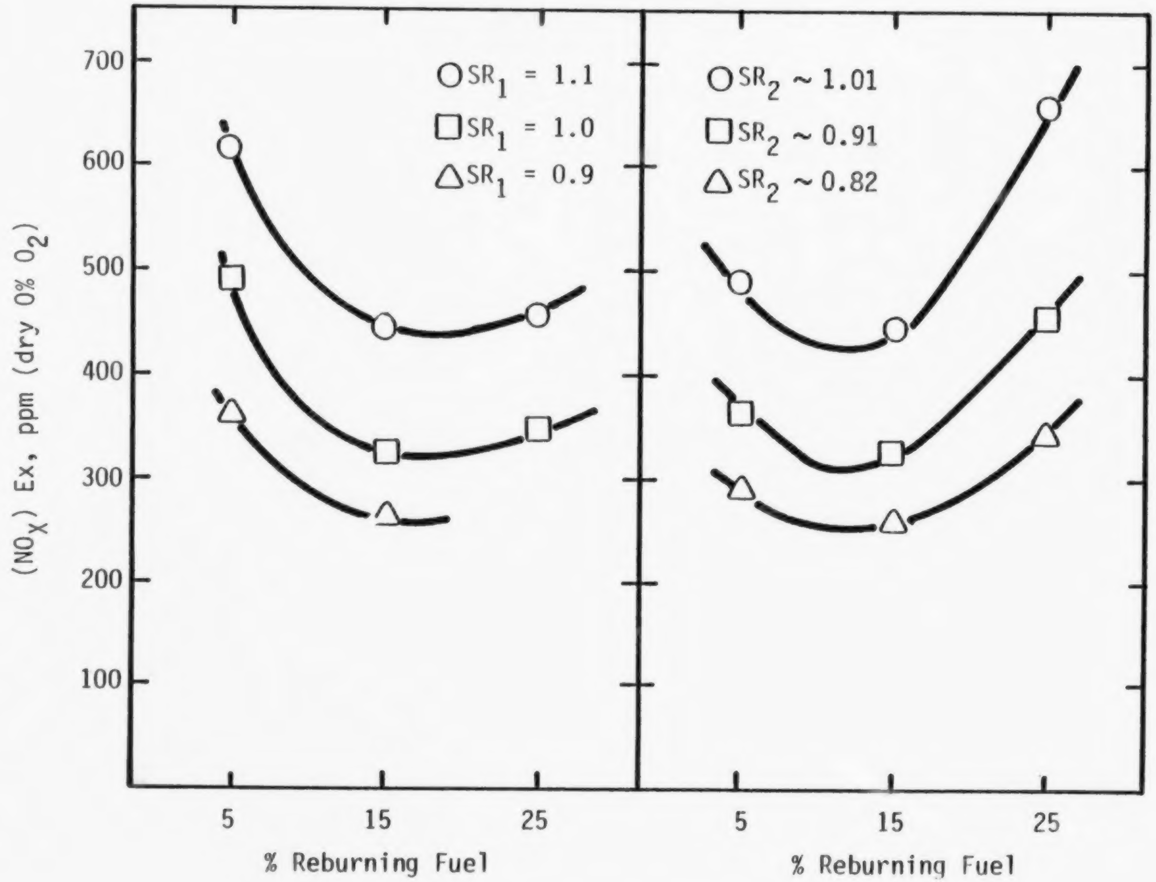


Figure 4-19. Primary NO_X influence for bench scale facility.



Profile 1
Utah/Utah
4, 2.8", 1 wall Reb Jets
Approximately 10% FGR

Figure 4-20. Influence of reburning fuel ratio on NO$_X$ emissions.

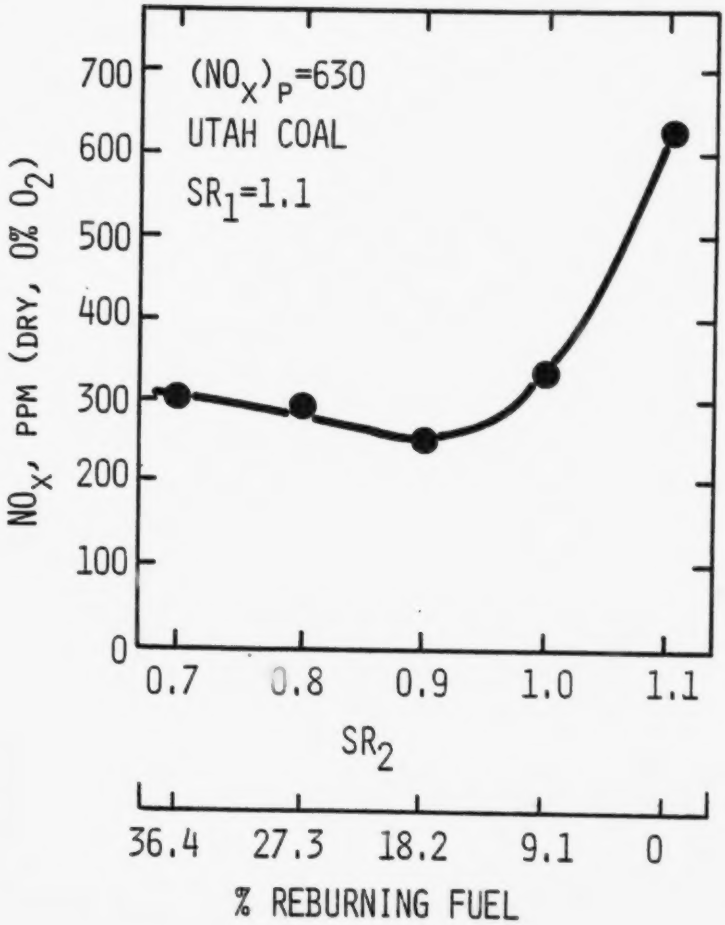


Figure 4-21. Reburning fuel ratio influence for bench scale facility.

load of about 15 percent of the total load was desired for minimum NO_x emissions.

In terms of full-scale boiler application, these data suggest that the main burners should be run at as low a stoichiometry as possible. The specific ratio used in real boilers will most likely be determined by the burner stability at low SR_1 values and the extent of slagging. Advantages of running low primary zone stoichiometries are that the peak flame temperature is increased, reburning zone residence time is increased, and primary NO_x formation is minimized.

4.10 Reburning Fuel Type

The effect of reburning fuel type on the reburning process is presented in Figure 4-22. Experiments were performed with natural gas as the primary fuel and either gas or Utah coal as reburning fuel. A similar injection configuration was used for both fuels in order to minimize mixing effects. From Figure 4-22, it is evident that natural gas performed better than coal when primary NO_x levels were low. This results was attributable to the absence of fixed nitrogen available for conversion to NO_x in natural gas.

In Figure 4-23, it is shown that tests performed on the CTT produced similar results. Experimental work was done at two levels of primary NO_x, with natural gas reburning yielding lower NO_x emissions in both instances.

4.11 Summary

Results obtained from process parameter studies showed that the impact of these parameters on the reburning process were independent of scale. The conditions which optimized the reburning process were as follows:

- Minimize transport oxygen (Flue Gas Recirculation)
- Minimize primary zone excess air

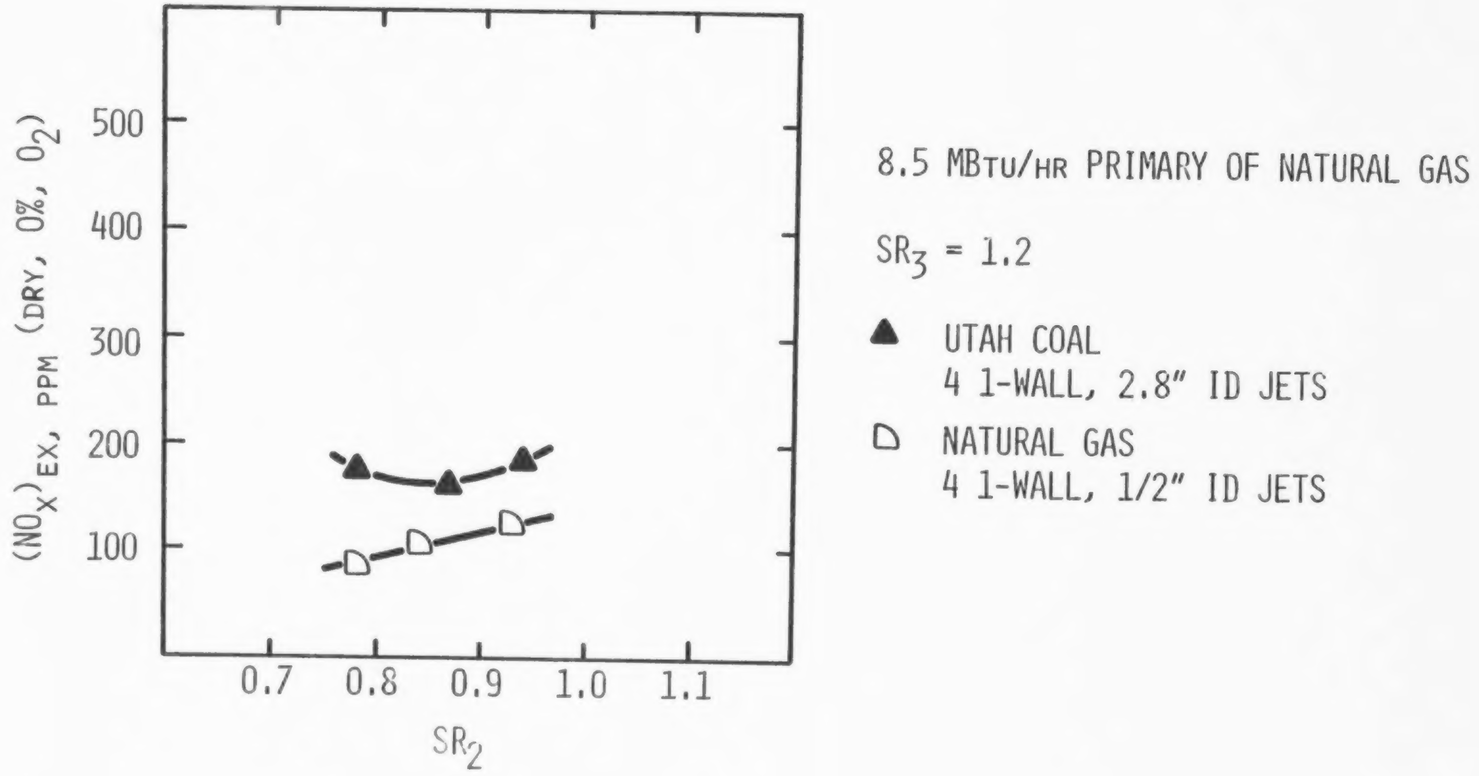


Figure 4-22. Influence of reburning fuel type on NO_X emissions.

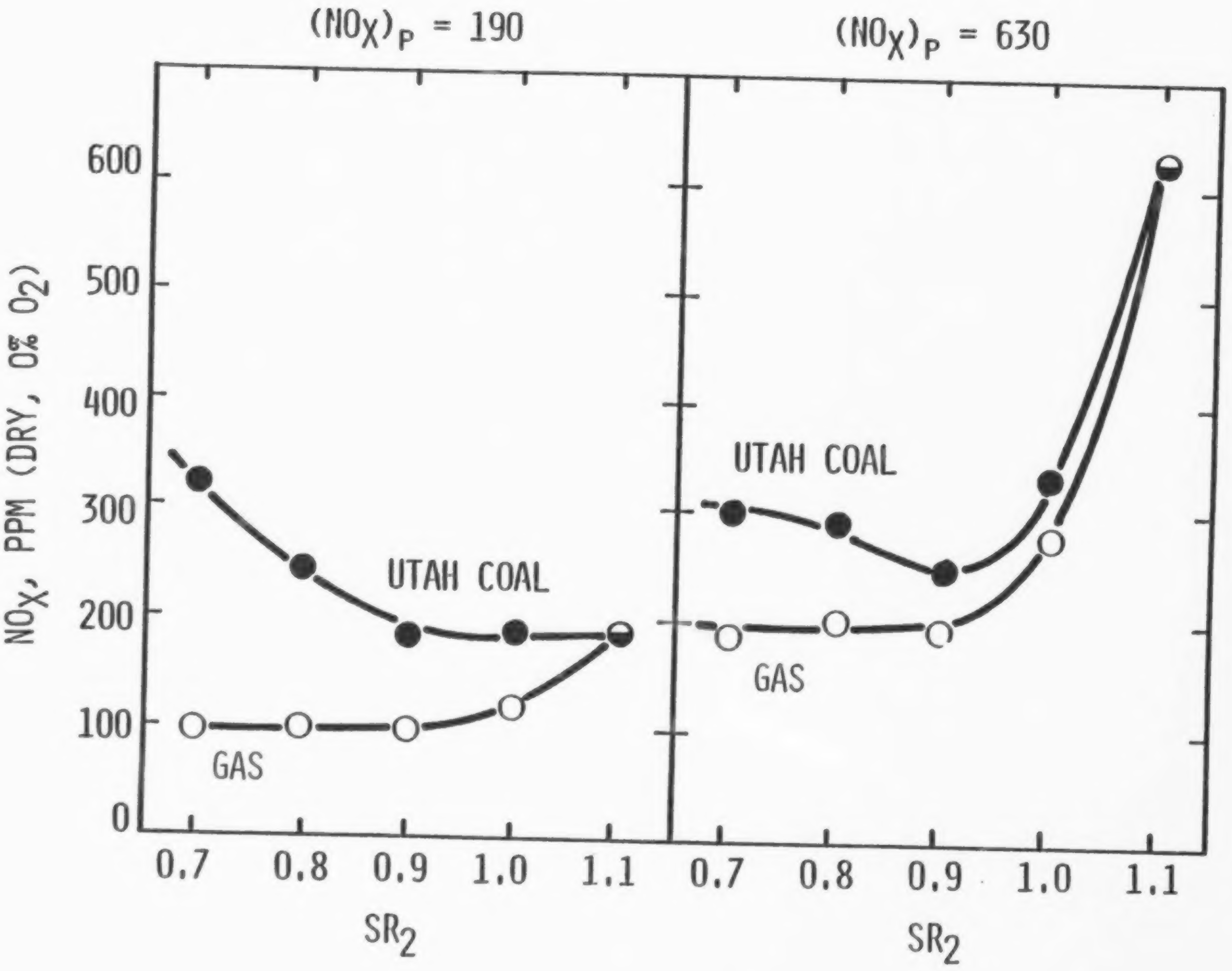


Figure 4-23. Influence of reburning fuel type for bench scale facility.

- Attain optimum reburning zone stoichiometry by utilizing approximately 20 percent reburning fuel
- Maximize reburning zone temperature
- Use natural gas as reburning fuel for low primary NO_x levels

5.0 MIXING STUDIES

This chapter discusses the results of those tests designed to study the effects of mixing on NO_x reduction. The parameters of interest includes reburning jet diameter and configuration, burnout air jet diameter and configuration, and reburning jet penetration into the main furnace flow. The results from bench scale mixing studies on the CTT are also included.

5.1 Bench Scale Mixing

Although the volume of the CTT was small and mixing rates were generally considered rapid under most conditions, several experiments were run in an attempt to define the role of mixing on NO_x reduction. The hardware used for these experiments is illustrated in Figure 5-1. In the CTT, the reburning zone was separated physically from the primary and burnout zones with the use of refractory chokes. The fuel and air injectors were positioned directly beneath the chokes as shown in the figure. Reburning fuel was injected beneath the upper choke in either a radial or axial fashion along the centerline of the furnace. Burnout air was injected beneath the lower choke through a ring with holes drilled either radially inward or axially downward in the furnace.

Figure 5-2 shows the results of these tests with Utah coal as the primary and reburning fuel. For the reburning fuel tests, radial injection (faster mixing) produced lower emissions than the slower mixing axial injection. In both cases, a minimum in emissions was exhibited at an SR_2 of 0.9. For the change in burnout air injection, no effect on NO_x was observed. These results will be compared to the large scale results in the following sections.

5.2 Burnout Air Mixing

On the Reburning Tower, which had a cross-sectional area of 16 ft^2, it was expected that the rate of mixing would have an impact on NO_x reduction for both air and reburning fuel injection. For the burnout air studies,

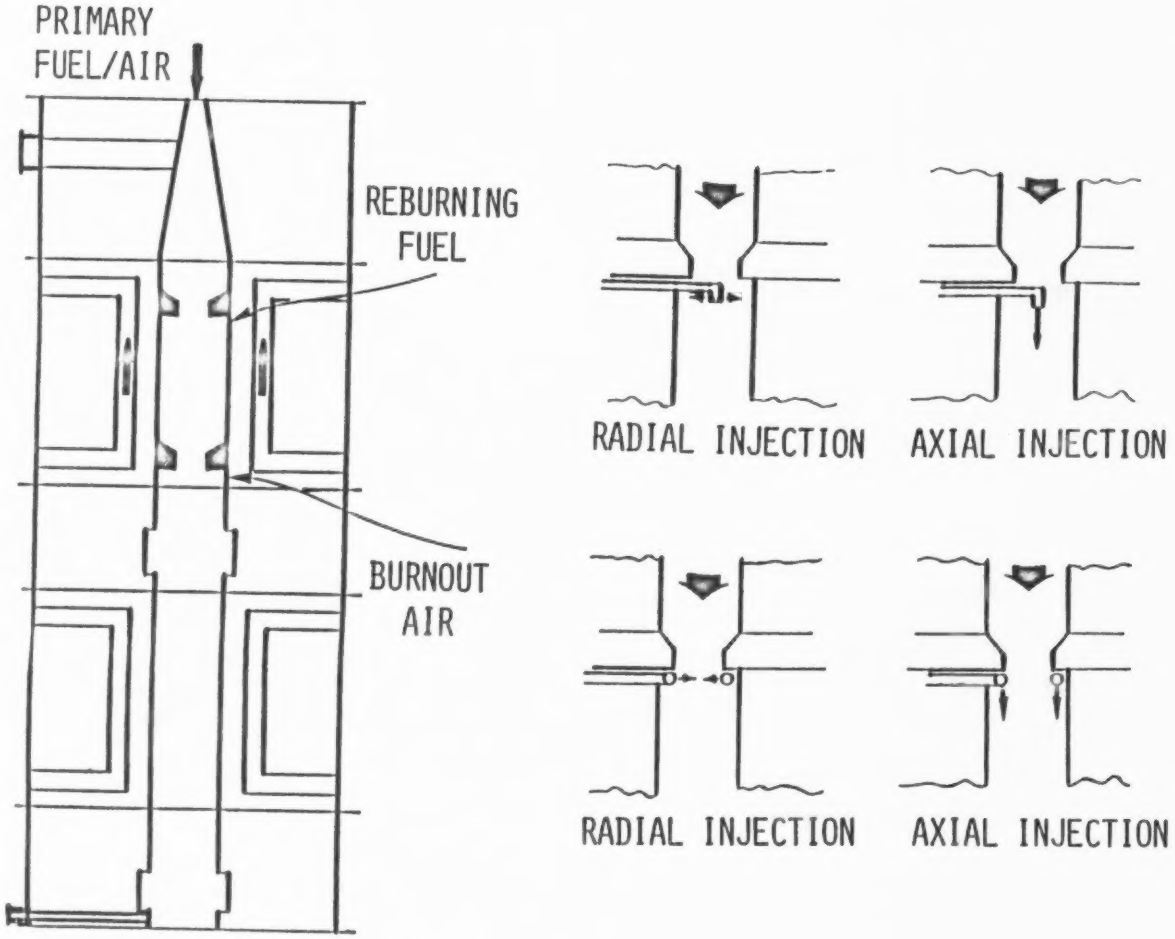

PRIMARY
FUEL/AIR
REBURNING
FUEL
BURNOUT
AIR
RADIAL INJECTION
AXIAL INJECTION
RADIAL INJECTION
AXIAL INJECTION

Figure 5-1. Bench-scale mixing configurations.

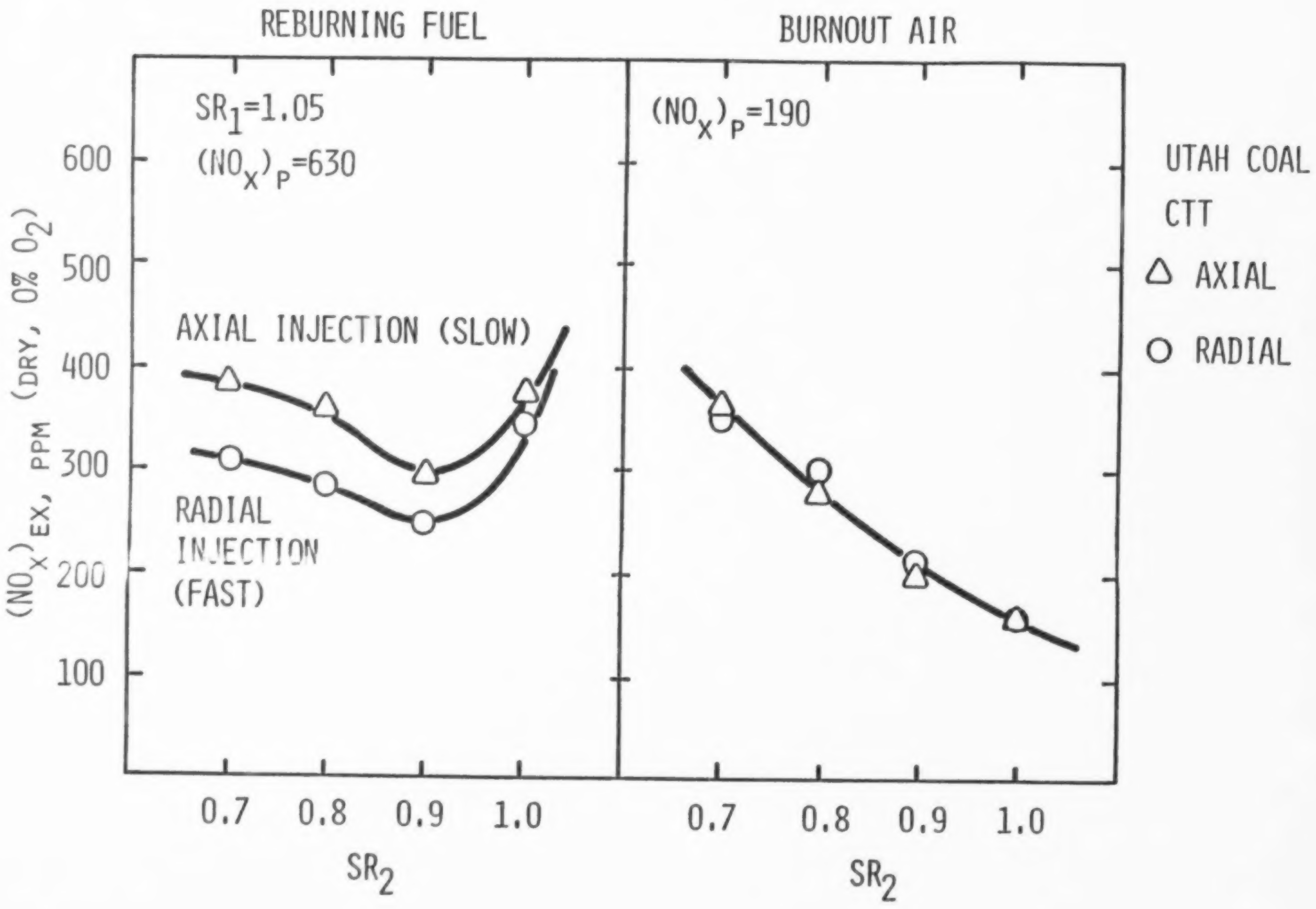


Figure 5-2. Bench scale mixing results.

three different configurations were used that gave a variety of mixing conditions. Figure 5-3 indicates the position and diameter of each jet for all of the configurations. The general approach in these experiments was to keep all flowrates and stoichiometries constant and vary only the position of the air entering the furnace. For each of the configurations, the total amount of air was constant and manifolds were used to distribute the flow in the cases with multiple jets. Figure 5-4 shows the results for four different injection schemes and indicates that 5-4 NO_x reduction was relatively insensitive to mixing rate. In the case of the 1-wall injection scheme, the larger jets (5.8" ID) gave slightly lower results than the smaller jets, which may have been due to the effect of penetration depth. Overall, the burnout air results gave the same trend as the bench scale data in that burnout air configuration was unimportant for NO_x control.

5.3 Reburning Fuel Mixing

The determination of an optimum reburning fuel injection scheme was of primary importance for this program. The effects of injector configuration and jet velocity (penetration) on mixing were investigated, as well as the effects of secondary parameters such as primary zone stoichiometry and reburning fuel ratio. Finally, detailed measurements at three planes within the reburning zone were completed to aid insight into the NO_x reduction process.

5.3.1 Operating Characteristics

Due to the deterioration of the insulation refractory in the furnace, the top two sections were recast and the furnace was characterized. The operating conditions and location of injectors used in the reburning fuel mixing studies and throughout the rest of the testing program are given in Figure 5-5 unless otherwise noted. Since recirculated flue gas was shown to be superior to air for transport of the reburning coal (see Chapter 4), the reburning fuel mixing studies were performed with flue gas recirculation (FGR) as the transport medium.

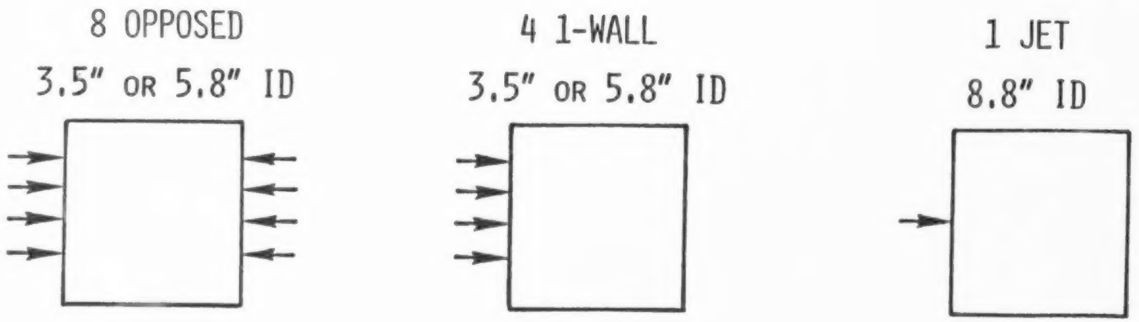

8 OPPOSED
3.5" OR 5.8" ID
4 1-WALL
3.5" OR 5.8" ID
1 JET
8.8" ID

Figure 5-3. Burnout air injection configurations.

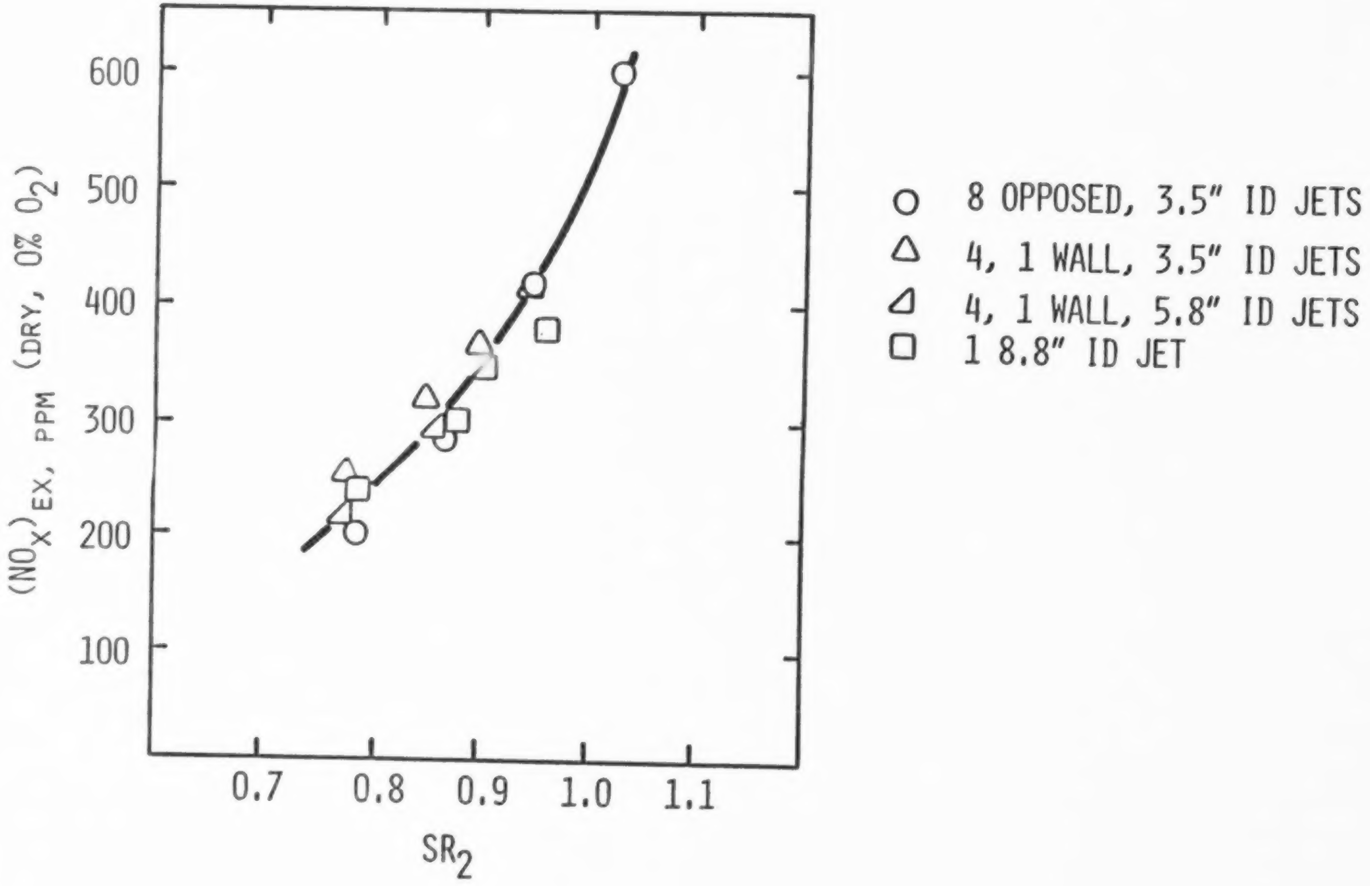
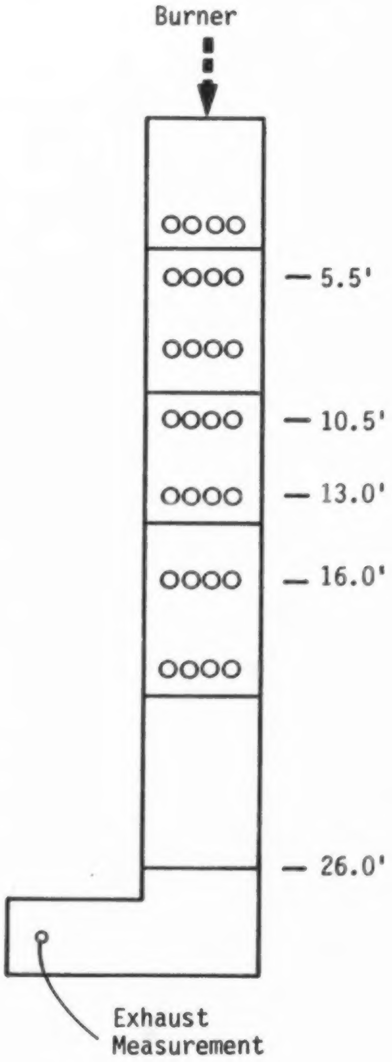


Figure 5-4. Effect of burnout air mixing rate.


Burner
OOOO
OOOO
OOOO
OOOO
OOOO
OOOO
OOOO
— 5.5'
— 10.5'
— 13.0'
— 16.0'
— 26.0'
Exhaust
Measurement

- Operation Conditions

10 MBtu/hr Total Load with Utah Coal
- 8.0 MBtu/hr Primary Load
- 2.0 MBtu/hr Reburning Load

Reburning Fuel Injection at 10.5'

- FGR Transport for Reburning Coal
- $T_{INJ} \sim 2550^{0}F$

Burnout Air Injection at 16.0'
- Four 5.8" ID Air Jets (1 Wall)
- $SR_T = 1.2$

Figure 5-5. Operating conditions for reburning fuel mixing studies.

Figure 5-6 shows the temperature profile obtained with 20 percent reburning fuel, four 2.8 in. ID jets on one wall of the furnace and 12 percent FGR for transport. The burnout air was injected into the furnace through four 5.8 in. ID jets, also located on one wall of the furnace. The Reburning Tower profile compares favorably with those of the actual boilers. Six cooling panels, two at level six and four at level seven, were utilized to achieve the desired quench rate in the lower end of the furnace. Figure 5-6 shows that the facility had a quench rate of about 400°F/sec between 2250 and 2000°F, with a quench rate of 300°F/sec present when the temperature range was extended down to 1700°F.

After characterization of the furnace thermal history, tests were run at several firing rates to determine the uncontrolled NO_x emissions. Excess air curves were run for loads of 10.0, 9.0, 8.0, and 7.0 MBtu/hr. The NO_x emissions which resulted are presented in Figure 5-7. The uncontrolled NO_x emissions rose with an increase in the excess air or firing rate. The arrow at approximately 3.6 percent O_2 represents the overall stoichiometry used during the reburning study. Percent NO_x reduction can be determined from the NO_x level with reburning relative to the uncontrolled emissions at the same overall stoichiometry.

The degree of primary fuel burnout prior to entrance into the reburning zone has a significant effect on the efficiency of the reburning process (See Chapter 4). For this reason, a radial composition and temperature traverse from the furnace centerline to wall was completed at the primary zone exit. The sampling location is shown in Figure 2-2. As shown in Figure 5-8, the temperature was approximately constant from the centerline to the wall. However, Figure 5-9 indicates that a composition gradient existed for each of the species measured. With 10 percent excess air, about 2 percent oxygen and 16.5 percent CO_2 were expected if burnout was complete. A radial average of the O_2 and CO_2 measurements indicated that these levels were approached and burnout was satisfactory. However, the non-uniform composition profile will lead to gradients in the reburning zone stoichiometry (SR_2) and have an adverse effect on NO_x reduction reactions in portions of the fuel-rich zone.

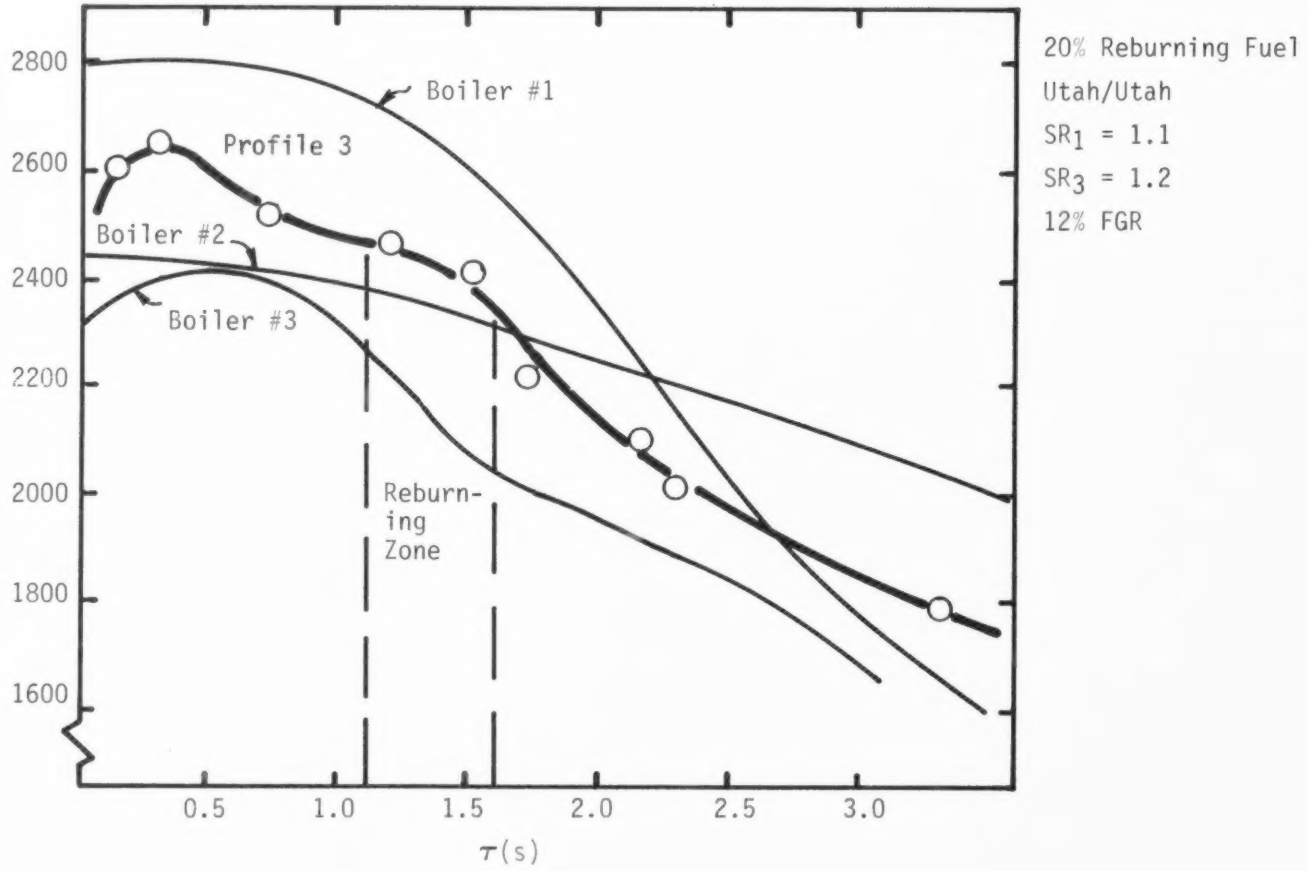


Figure 5-6. Reburning Tower temperature profile.

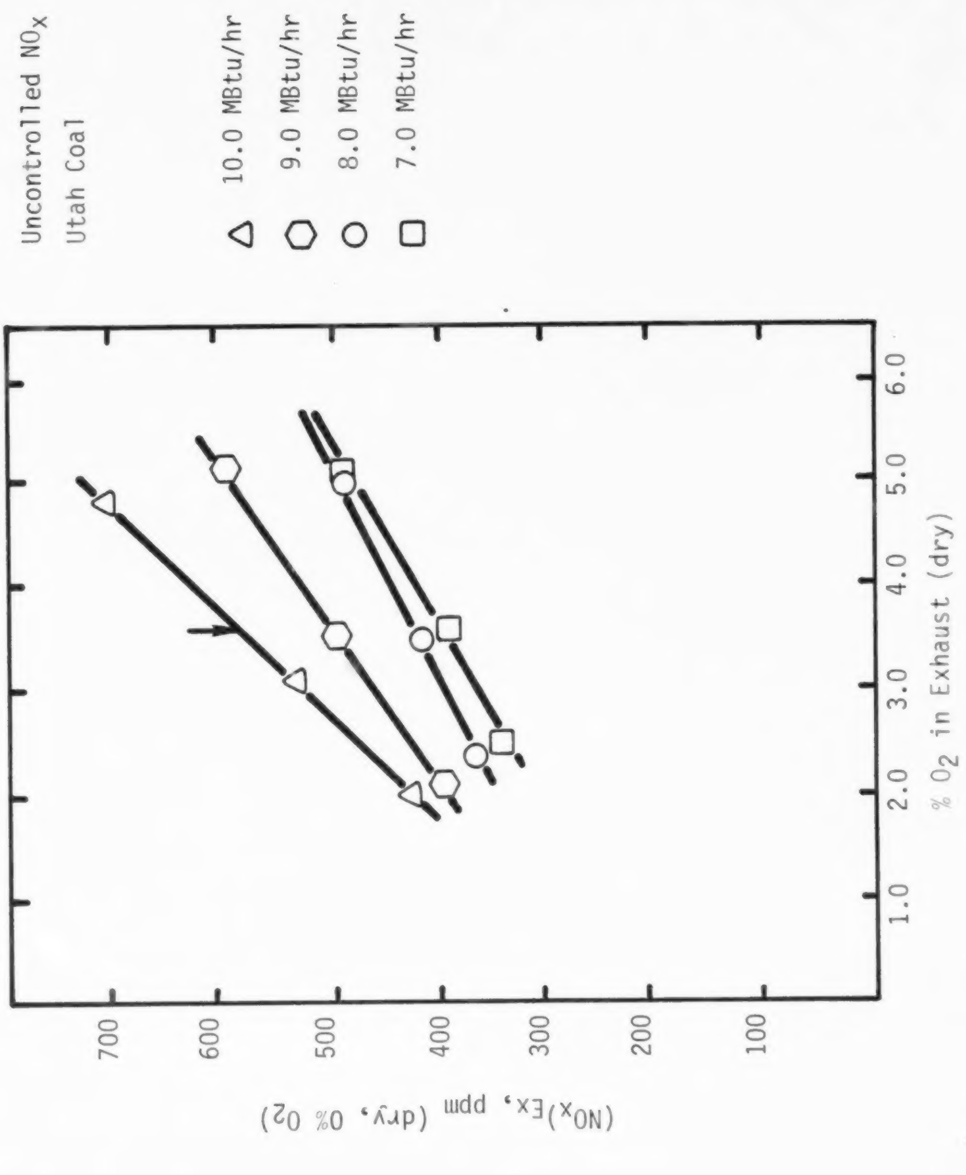


Figure 5-7. Effect of excess O_2 on uncontrolled NO_x emissions.

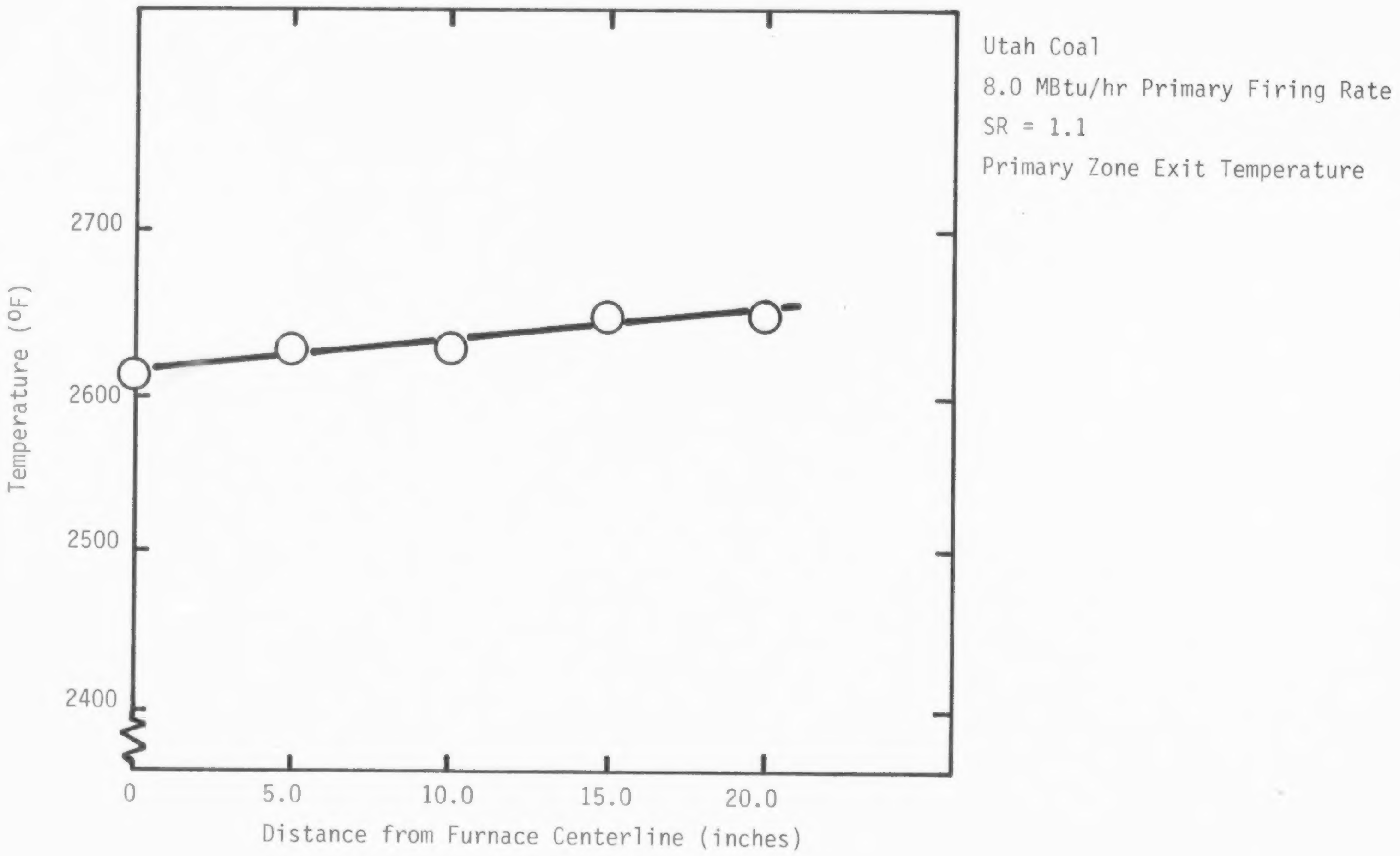


Figure 5-8. Primary zone exit radial temperature profile.

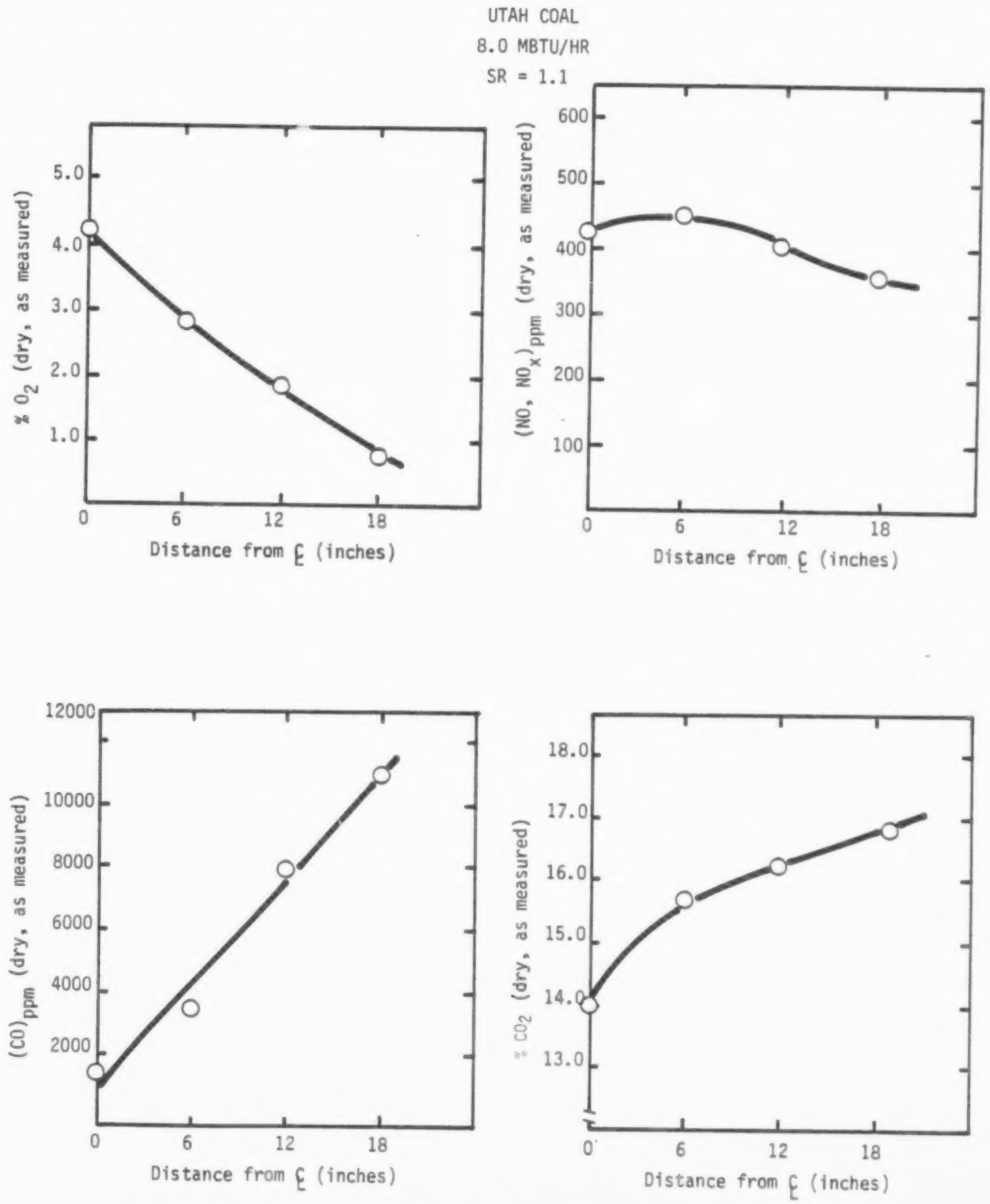


Figure 5-9. Primary zone exit radial composition profile.

This effect will be examined in more detail in sections which pertain to the detailed mapping of the reburning zone.

5.3.2 Jet Configuration and Penetration

In order to study the effects of mixing for a given reburning configuration (i.e. 15 percent reburning fuel at 10.5 ft and air at 16 ft), a variety of injection schemes were employed. The three configurations used for the first series of experiments are illustrated by Figure 5-10. The first configuration involved eight opposed 1.7 in. ID jets with four on each of two walls, the second was four 2.8 in. ID jets on one wall of the furnace, and the last configuration consisted of a single 8.8 in. jet located in the center of one wall. For each setup, the total air or flue gas flowrate was again held constant, however, jet velocities, penetration depths, and entrainment rates varied. Thus, any variation in NO_x emissions could be directly linked to mixing pehnomenon rather than chemical effects.

With the burnout air configuration held constant, the reburning fuel injection configuration was varied by the three injection schemes described in Figure 5-10. The NO_x emissions results for the different configurations are shown in Figure 5-11 as a function of SR_2. Of the three cases, the four one-wall jets produced the lowest emissions. These data were obtained at a constant FGR flow rate of 10 percent. In order to examine the impacts of the FGR flowrate, the reburning coal delivery system was modified to allow for the use of various amounts of percent FGR for transport. Experiments were then carried out with 20 percent reburning fuel using the three injection configurations shown in Figure 5-12. The NO_x emissions obtained for these configurations, shown in Figure 5-13, indicated that the four one-wall jets produced the lowest emissions, while a significant increase in NO_x emissions occurred when the staggered configuration was employed.

The data presented in Figure 5-13 is plotted with percent FGR as the independent variable. For each flue gas recirculation ratio there was an associated jet velocity and thus jet penetration into the furnace. Observed jet penetration agreed favorably with values calculated via an empirical

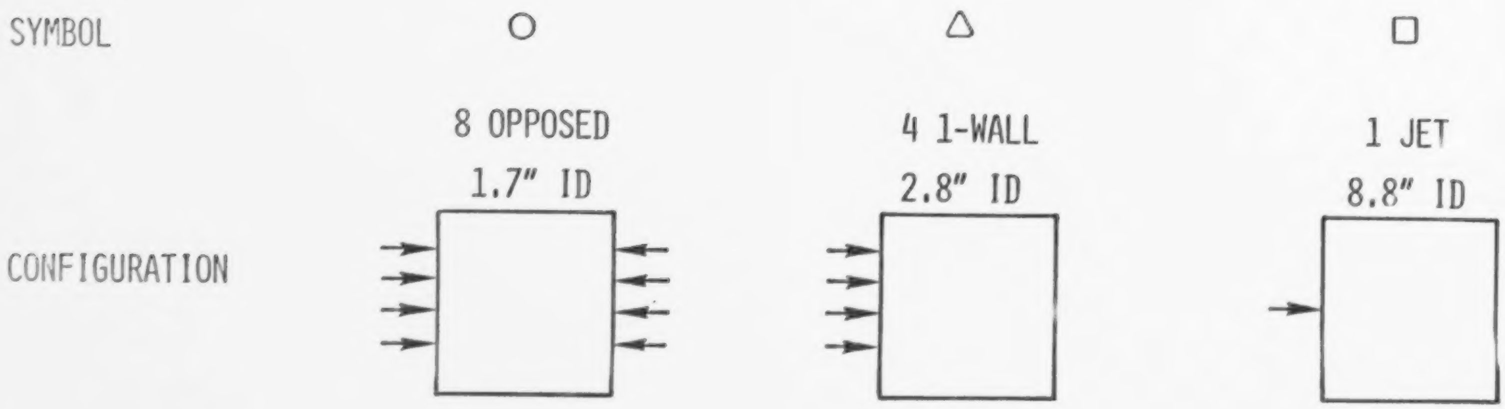

SYMBOL
CONFIGURATION
○
8 OPPOSED
1.7" ID
△
4 1-WALL
2.8" ID
□
1 JET
8.8" ID

Figure 5-10. Reburning jet configurations.

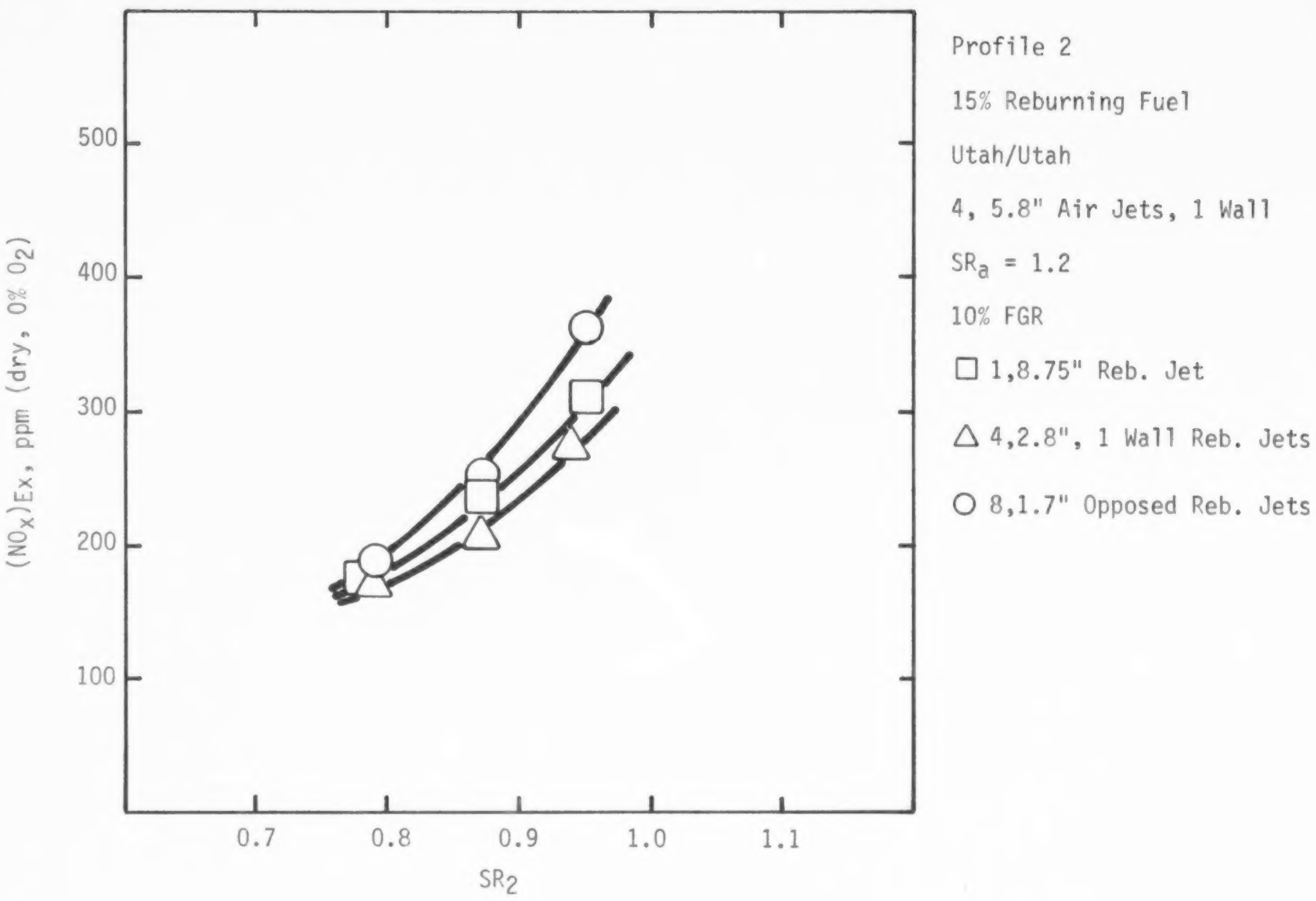


Figure 5-11. Effects of reburning fuel configuration.

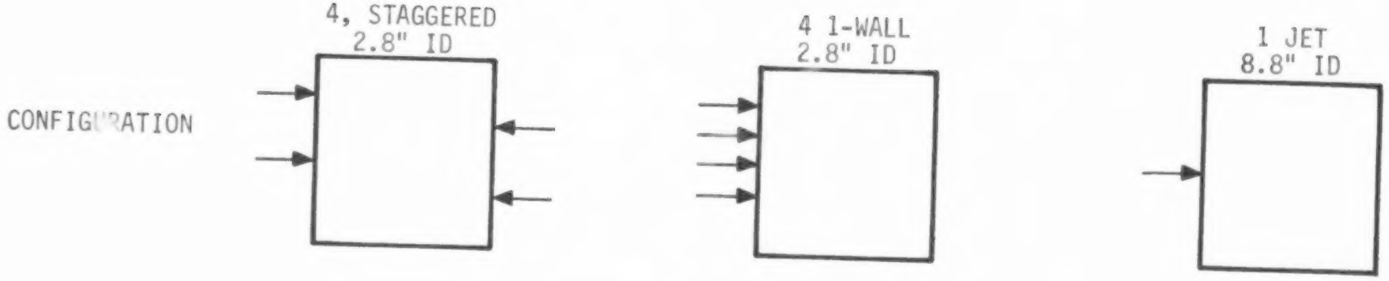

CONFIGURATION
4, STAGGERED
2.8" ID
4 1-WALL
2.8" ID
1 JET
8.8" ID

Figure 5-12. Reburning fuel injector configurations.

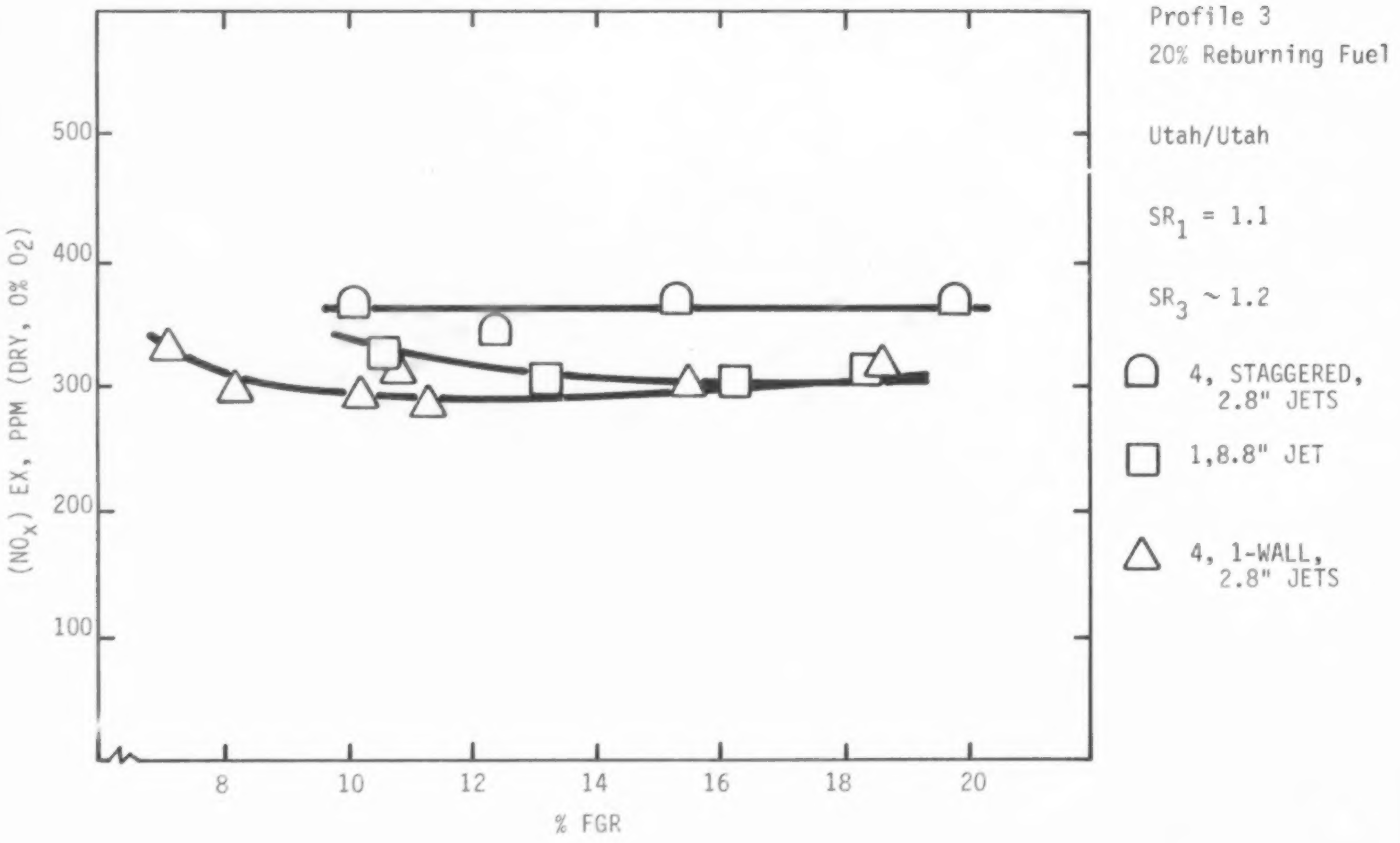


Figure 5-13. Effect of reburning fuel injection configuration on NO_x emissions.

correlation for penetration developed by Shandarov, as cited by Abramovich (1963), with the correlation tending to slightly underpredict the actual penetration. Data shown in Figure 5-13 are presented again in Figure 5-14 with calculated jet penetration depth plotted on the abscissa. Both one and four wall-fired jets exhibited a similar trend: the level of exhaust NO_x remained fairly constant once a minimum penetration depth was exceeded. However, a different minimum penetration was required for the two configurations. Complete penetration was required with one large jet while four jets, which provided better coverage of the furnace cross-sectional area, needed to penetrate to about 70 percent of the furnace depth for minimal emissions. Although a further increase in the penetration of the four jets increased mixing, any enhancement in NO_x reduction induced by this was countered by the detrimental effect of a rise in the reburning zone stoichiometry which accompanied increased FGR flowrates.

5.3.3 Coupling with Other Parameters

Figure 5-15 illustrates the effect of reburning jet penetration depth on NO_x emissions for two values of primary NO_x. With a lesser amount of NO_x exiting the primary zone, penetration depth had no effect on NO_x emissions. This was not the case for higher values of $(NO_x)_p$, as shown in Figure 5-15. An increase in the reburning jet penetration depth corresponded to an increase in mixing for the range of penetration and configurations shown in Figure 5-15. For $(NO_x)_p$ destruction, it is desirable for mixing to be fast so that the primary NO_x has a longer residence time in the fuel-rich zone. With higher primary NO_x values, this mixing effect is more prominent, which can account for the results shown in Figure 4-15.

The impacts of injection configuration were also examined at various reburning fuel ratios. As shown in Figure 5-16, the results are similar for 25 and 15 percent reburning fuel ratios. NO_x emissions are in the range of 175-325 ppm, depending on SR_2, and little difference was evident between the two reburning fuel configurations utilized. With 5 percent reburning fuel, the results differ. A 50-100 ppm difference was observed between the two configurations, and NO_x emissions were lower for the other two reburning

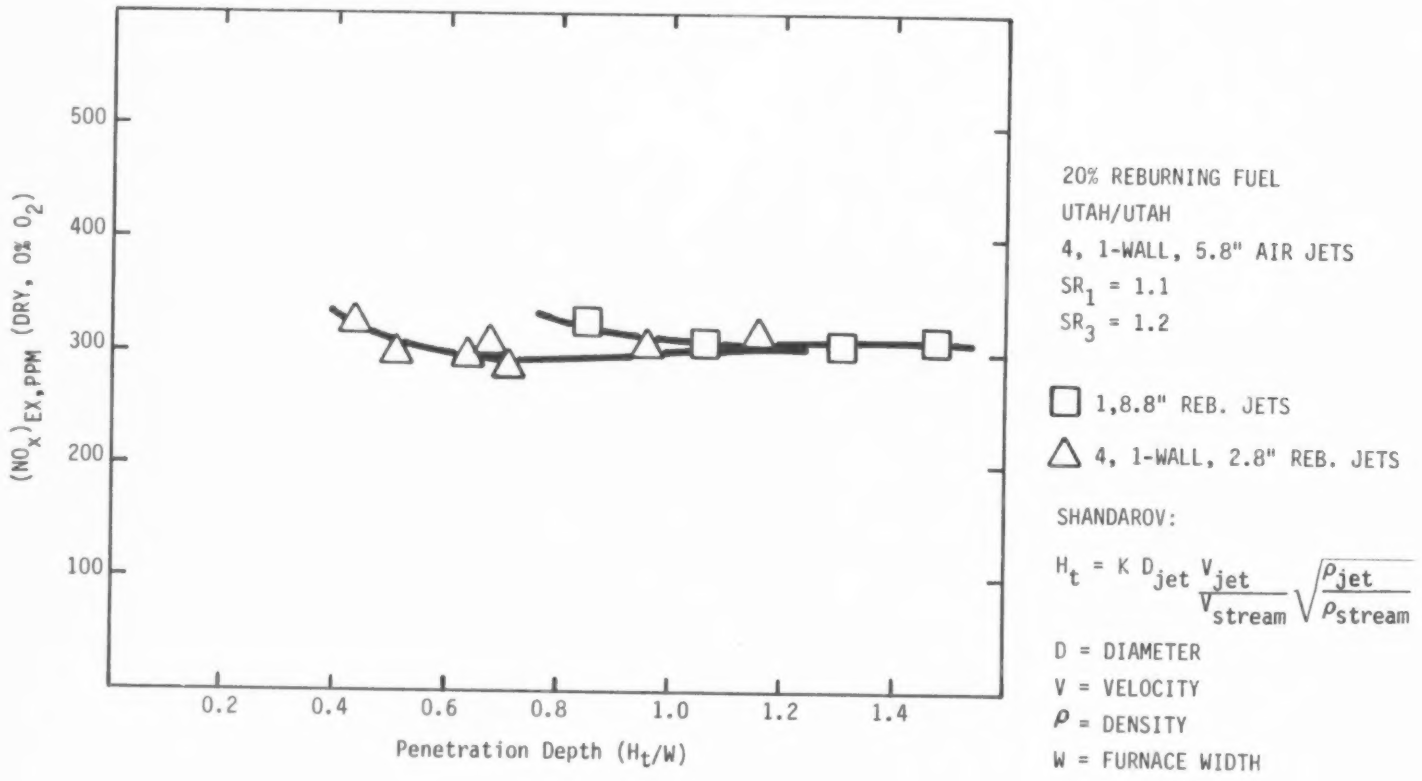


Figure 5-14. NO_x emissions vs. jet penetration depth.

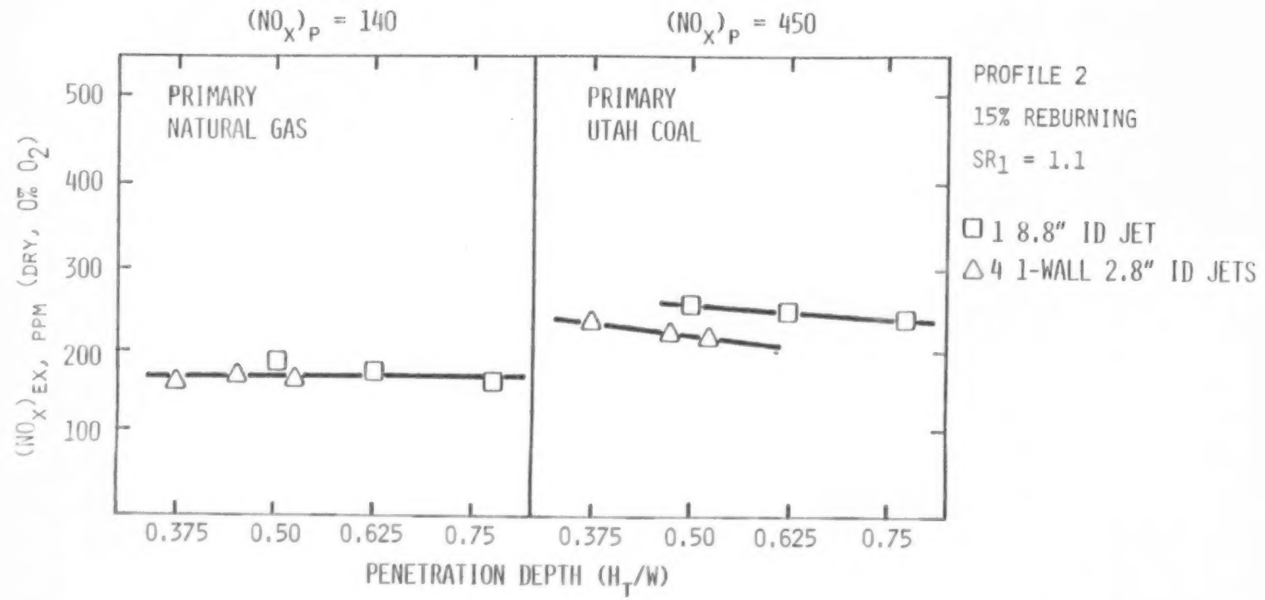


Figure 5-15. Influence of $(NO_X)_p$ on mixing effects.

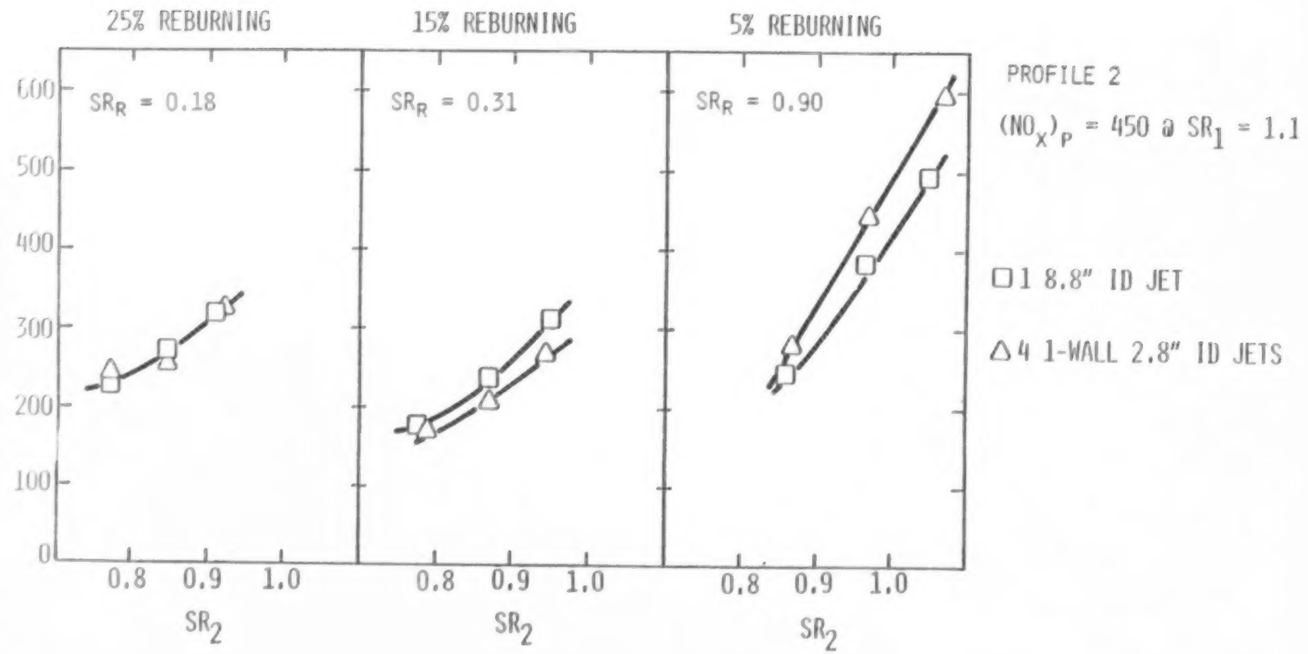


Figure 5-16. Influence of stoichiometry on mixing effects.

loads. This effect was caused by the reburning transport line stoichiometry, $(SR)_r$. With five percent reburning fuel, $(SR)_r$ was quite high relative to that for the other loads. A substantial $(SR)_r$ effectively transforms the reburning injectors into premixed burners which result in higher NO_x emissions. The fact that mixing between the O_2 and reburning fuel is more complete in four jets than one large jet accounts for the higher emissions observed when four wall-fired injectors are used.

It can be seen from the data shown in Figure 5-16 that the impacts of mixing (injection configuration), regardless of the reburning fuel ratio, were less prominent at richer reburning zone stoichiometries (SR_2). This phenomenon was further investigated for the 5 percent reburning fuel case. Experiments were carried out at two primary stoichiometries, i.e., 1.0 and 0.9, and the amount of FGR was varied from 6 to 13 percent. Figure 5-17 presents these data. At an SR_1 of 1.0, not only were the NO_x emissions higher than for 0.9, but emissions increased faster for a given increase in percent FGR, due to a corresponding increase in SR_r, and thus the SR_2. At an SR_1 of 0.9, where the reburning zone was much richer, the four injector configuration curve was much flatter and for the single jet, emissions actually decreased slightly with increasing FGR.

The impacts of injection configuration at high reburning fuel ratios, i.e. 30 percent, are illustrated in Figures 5-18 and 5-19. At a common percent FGR with 30 percent reburning fuel, there was little difference in NO_x emissions between the two configurations. However, when emissions were compared at a common penetration depth, as in Figure 5-6, four wall-fired jets proved to be more efficient at NO_x reduction. Since the single jet rebounded off of the opposite wall for all of the data taken, reburning zone mixing was enhanced. This caused the NO_x reduction capabilities of one jet to compare with that of four jets at an equivalent FGR flowrate.

With 30 percent reburning fuel, NO_x emissions continually decreased as the transport medium flowrate increased. This indicated that mixing had a more important role when larger amounts of reburning fuel were used. A possible factor in this result could be reburning zone stoichiometry effects.

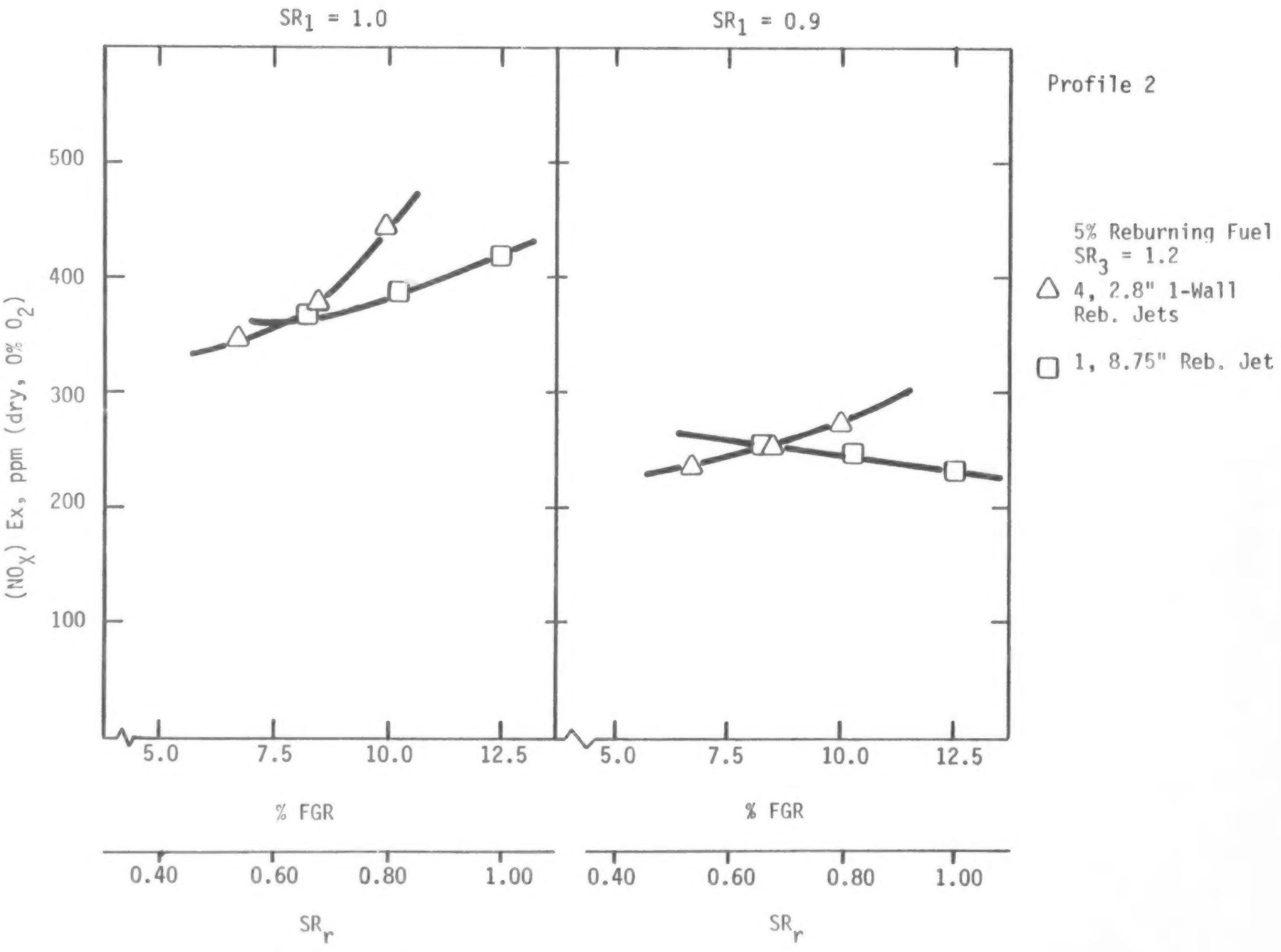


Figure 5-17. Influence of SR_2 and SR_r on mixing effects.

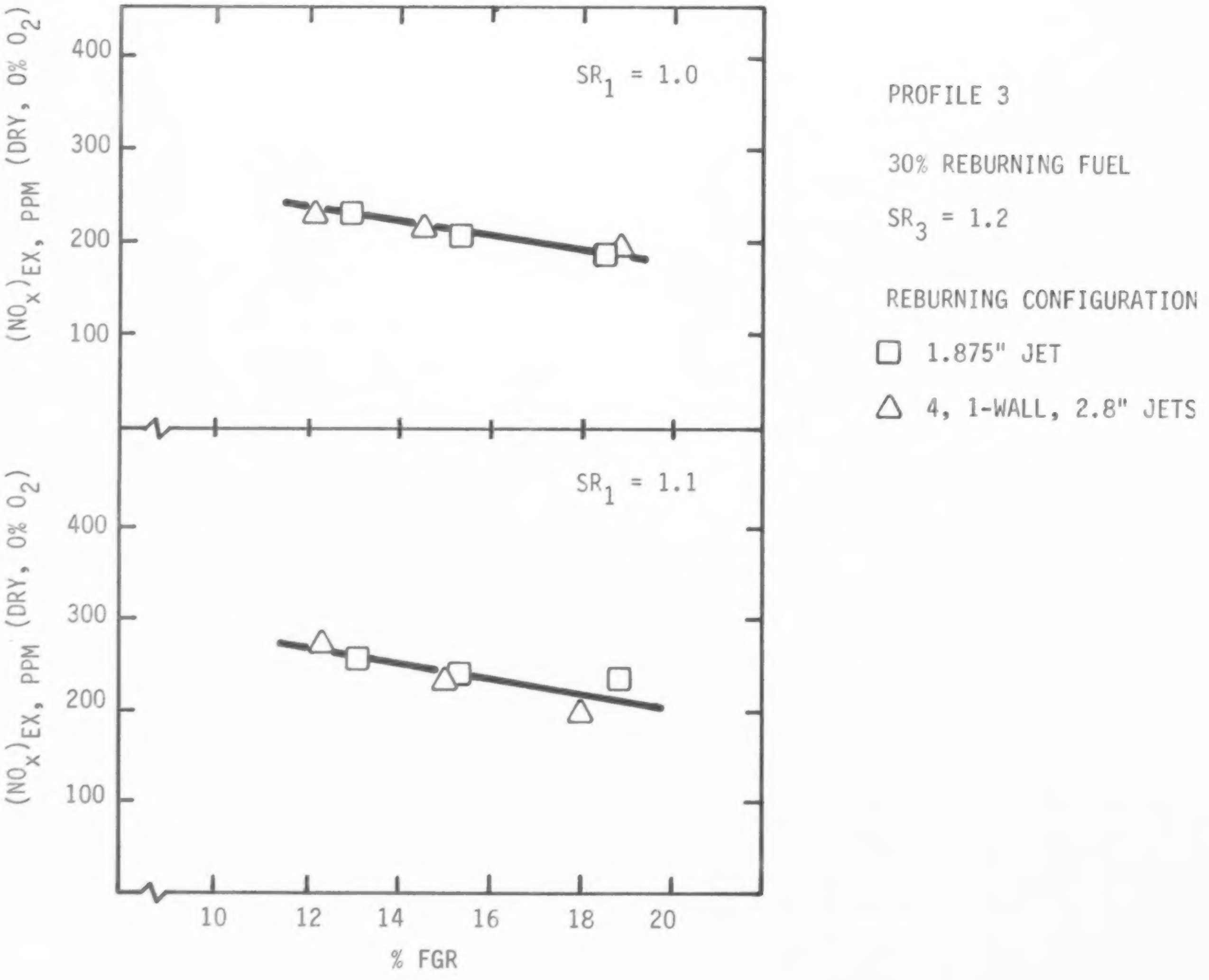


Figure 5-18. Influence of mixing at high reburning fuel ratios based on FGR flowrate.

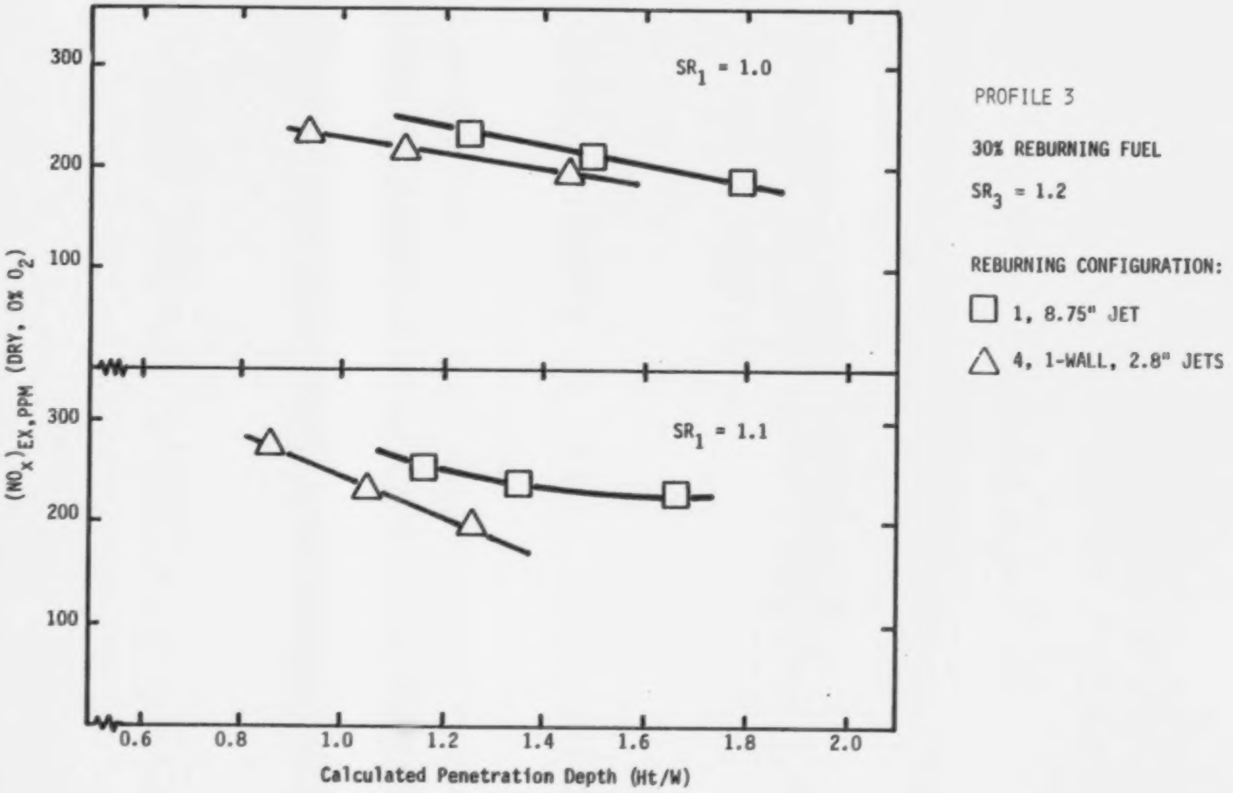


Figure 5-19. Influence of mixing at high reburning fuel ratios based on jet penetration.

Previous work has shown that NO_x reduction is optimal when the reburning zone stoichiometry is about 0.9 (Greene, et al., 1984. With 30 percent reburning fuel, stoichiometries below this level were attained. Thus, as FGR flowrates increased, the resultant increase in reburning zone stoichiometry would have no longer been a detriment and may have been advantageous to NO_x reduction. This fact, combined with enhanced mixing caused by deeper jet penetration and turbulence from jets which struck the opposite wall, could account for the constant decrease in emissions with FGR flowrate increases. Although NO_x emissions were lower at high FGR flowrates, the deterioration of furnace hardware due to the slagging caused by over-penetration of fuel jets makes a lesser penetration appear more desirable.

5.4 Reburning Zone Mapping

In order to gain better understanding of the processes which occur in the reburning zone, a concentration map of the furnace cross-section was obtained at three planes in the Reburning Tower (see Figure 2-2). Concentrations of O_2, CO_2, CO, NO and THC were measured at 16 points in each plane. At level four, the reburning zone entrance, mapping was completed without reburning to characterize the profile from the primary zone combustion products. Reburning was then applied, and levels five and six, the usual reburning zone exit location, were mapped. Burnout air was moved to level seven for the tests. Temperature measurements were also taken and were consistent ($\pm 20^{\circ}F$) across the furnace cross-section for each level.

5.4.1 Reburning Zone Entrance Map

The concentration profiles for O_2, CO, NO and THC at level four are shown in Figure 5-20. The concentration maps indicated a non-uniform flame front. Although it was visually confirmed that each of the four main burner injectors fired, it is possible that fuel was not evenly distributed among the injectors. It is also conceivable that inconsistencies in the furnace contour due to slag buildup in certain regions altered flow patterns in the furnace.

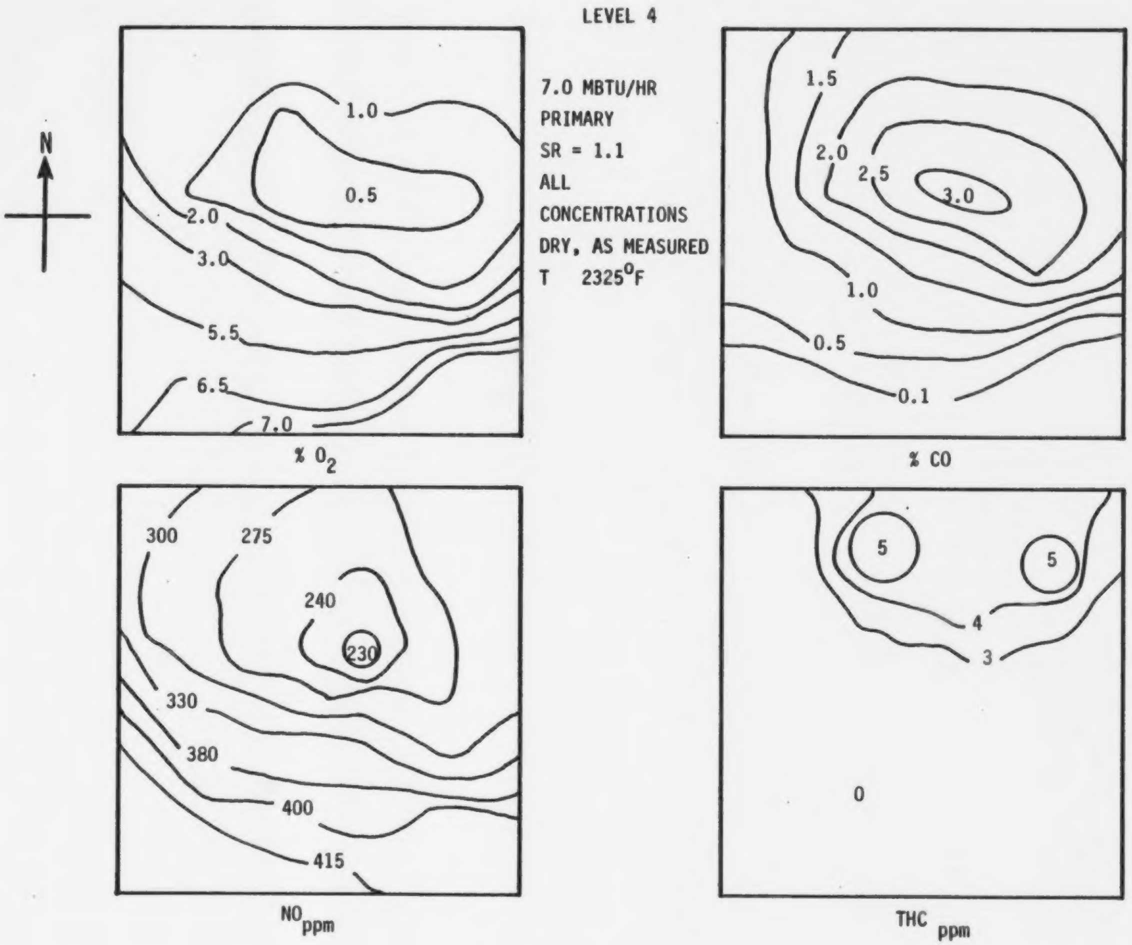


Figure 5-20. Reburning zone entrance concentration map.

The insignificant THC amounts measured indicated combustion of the primary fuel had proceeded well, but high CO concentrations implied that burnout was not yet complete. As expected, low oxygen concentrations present in the locally fuel-rich zone at the furnace north end coincided with low NO and high CO amounts.

5.4.2 Mid-Reburning Zone Map

The concentration profiles obtained at level five are presented in Figure 5-21. The reburning fuel was injected through four jets on the west wall of the furnace. Relatively high O_2 and NO, and low CO and THC measurements near the east wall indicated that the jets had not yet penetrated completely across the furnace. A fairly even fuel split among the four jets was visually observed, and reduction in O_2 concentrations from level four to five in the west end of the furnace verify that the reburning fuel injected was distributed well between the jets.

The non-uniform oxygen profile of the primary zone effluent led to SR_2 gradients in the reburning zone. The north end of the furnace had less oxygen, thus NO species from the primary zone were able to compete with O_2 for hydrocarbon radicals, and considerable NO reduction occurred (compare Figures 5-20 and 5-21). In the furnace south end, NO could not contend with the high levels of O_2, and hydrocarbon radicals had a tendency to oxidize rather than reduce NO. The CO and THC measurements indicated that notable amounts of unburned fuel were present near the center of the furnace. This suggests that the reburning jets cut through the plane at level five about midway across the furnace. This large hydrocarbon pool was available for further reduction of NO, which was evident when mapping was completed at level six.

5.4.3 Reburning Zone Exit Map

The concentration maps obtained at level six are presented in Figure 5-22. Diminished concentration gradients from the west to east walls implied that the reburning jets were well dispersed by the time the

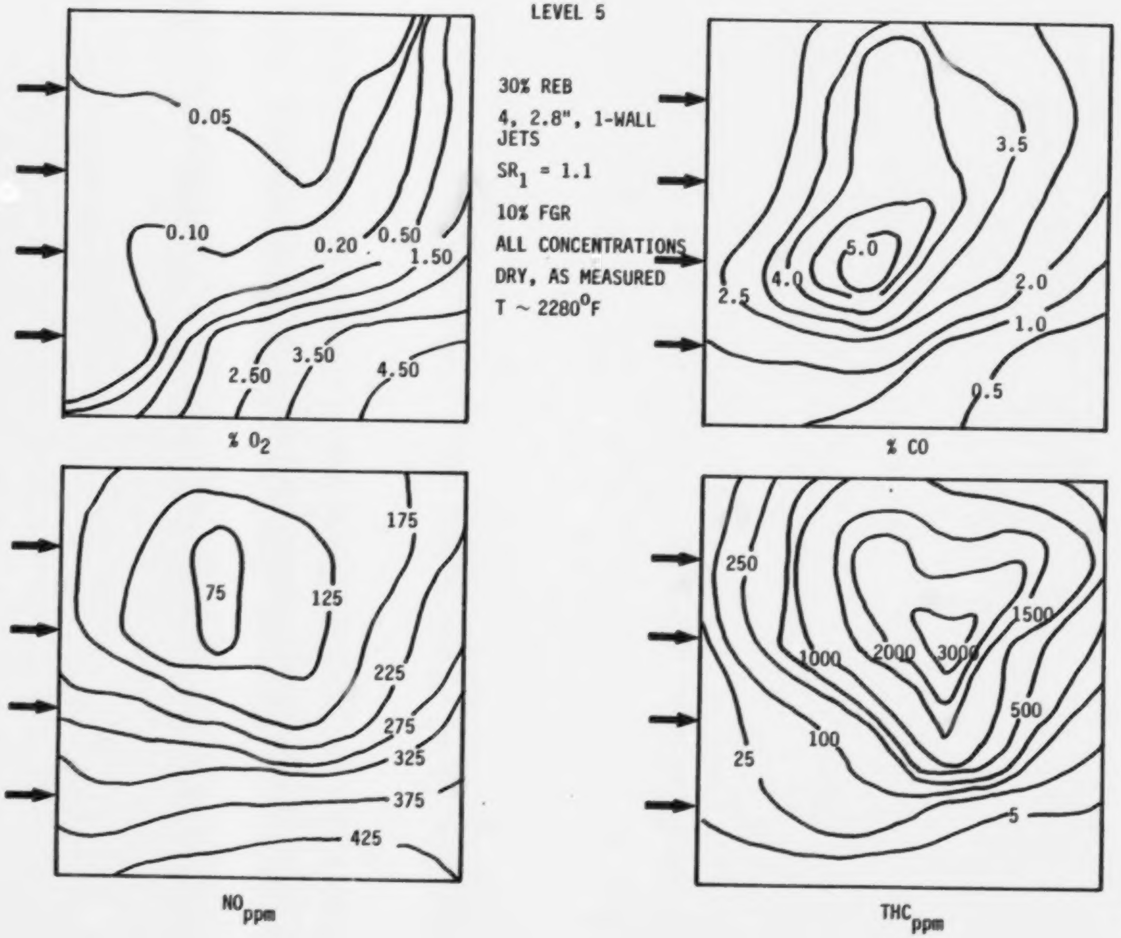


Figure 5-21. Level five concentration map.

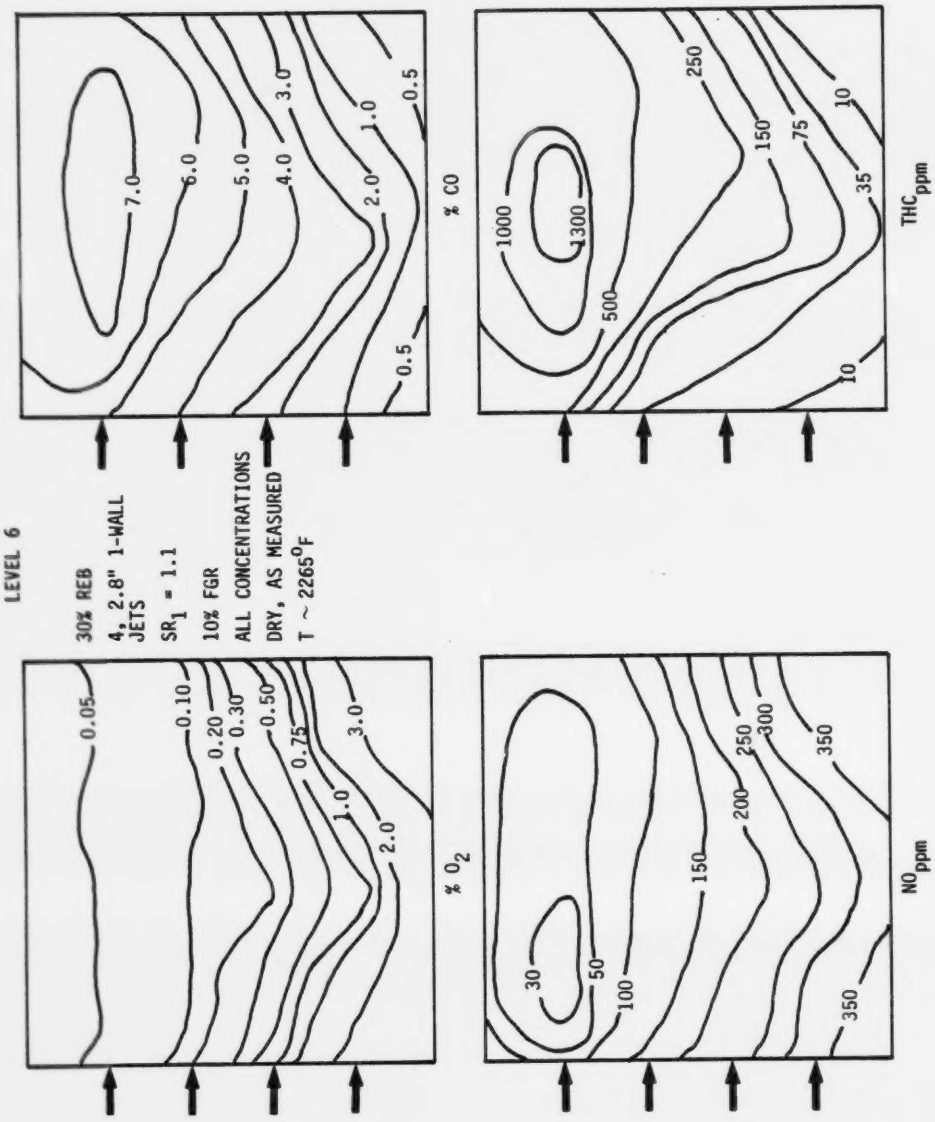


Figure 5-22. Reburning zone exit concentration map.

combustion products reached the usual burnout air location. Once again, significant NO reduction occurred in the section of the furnace with low O_2 concentrations. The substantial amount of oxygen present in the southeast corner of the furnace limited NO reduction in that area.

The reduction of both NO and THC amounts from level five to six indicated that the conversion of NO to molecular nitrogen via reaction with nitrogen radicals has proceeded (see Figure 1-1). Higher CO levels throughout the furnace coupled with the decreased NO measurements suggested that oxygen freed upon NO reduction was utilized in the oxidation of hydrocarbons.

For easier reference, the progressions of O_2, NO, CO and THC compositions from level four to level six are presented in Figures 5-23, 5-24, 5-25 and 5-26 respectively.

It is not certain if a uniform primary zone exit composition profile would benefit overall NO reduction. The high levels of NO reduced in oxygen deficient zones may be enough to counterbalance the lack of reduction which occurred in the locally fuel-lean zones. About 2 percent O_2 was expected at the primary zone exit if combustion was complete. If the volume element which contained a constant concentration of 2 percent O_2 at the primary zone entrance is traced through the reburning zone, O_2 drops close to zero percent and NO decreases from about 310 ppm to 170 ppm. If NO concentrations measured across the furnace cross-section are averaged at levels four and six, they would approach these values (315 and 155 ppm at 2.4 and 0.5 percent O_2 respectively). These assumptions are uncertain, and further investigation into non-uniform composition profiles would be necessary to ascertain its true effect on NO reduction capabilities.

5.5 Summary

The results of the mixing studies indicated that in general, mixing parameters were not as important for overall NO_x reduction as the chemical and thermal parameters outlined in Chapter 4.0. However, some injection

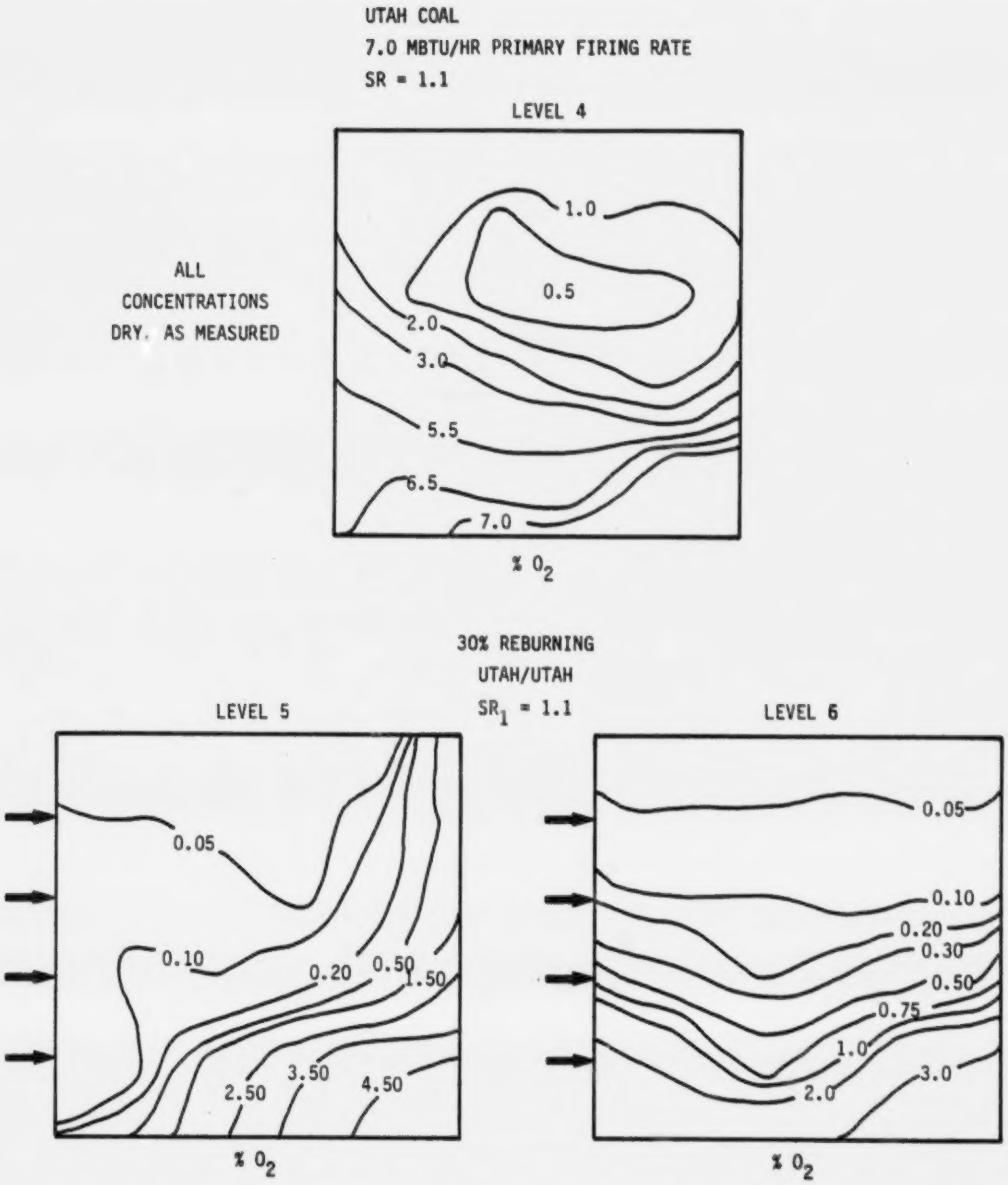


Figure 5-23. Reburning zone O_2 map.

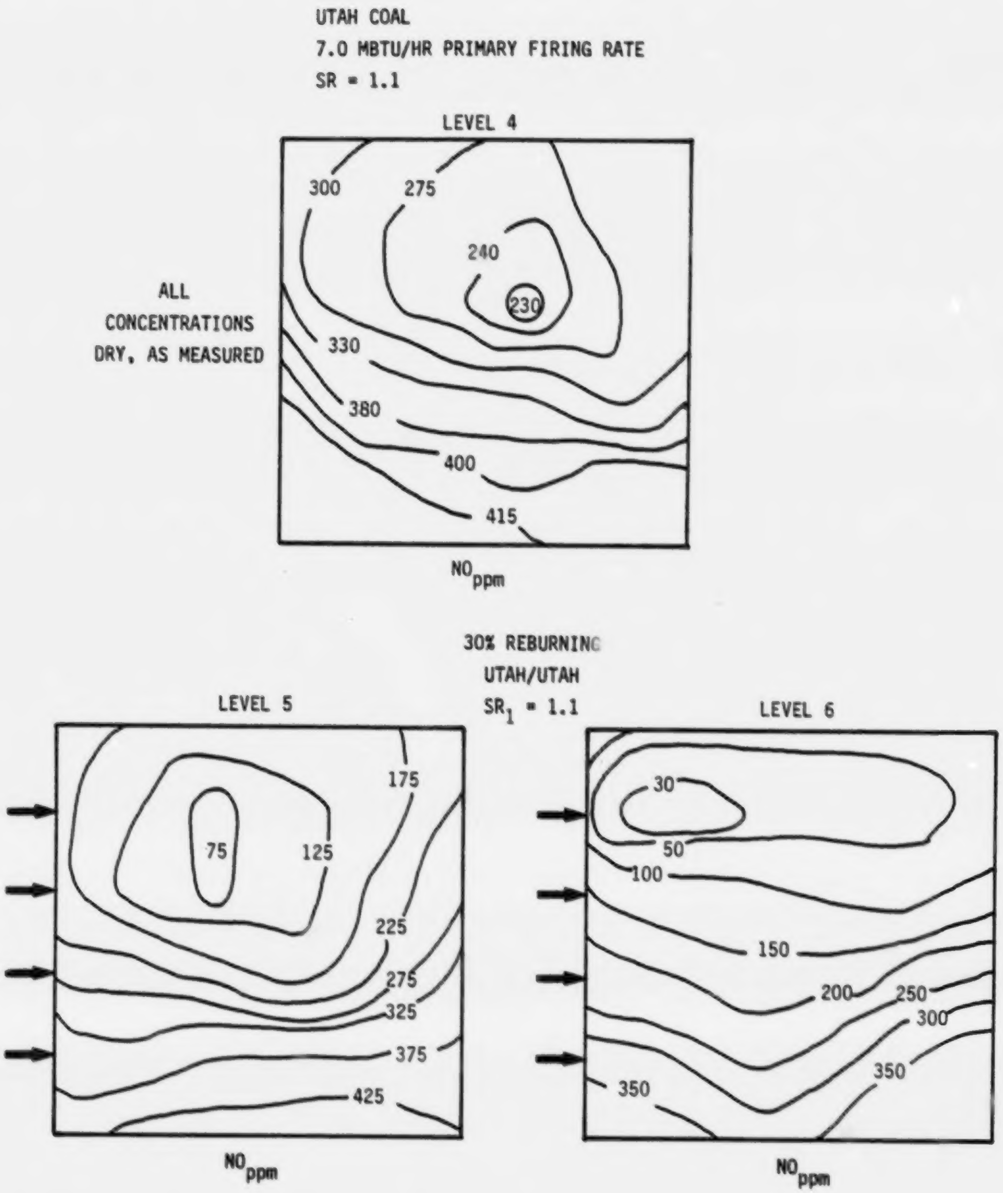


Figure 5-24. Reburning zone NO map.

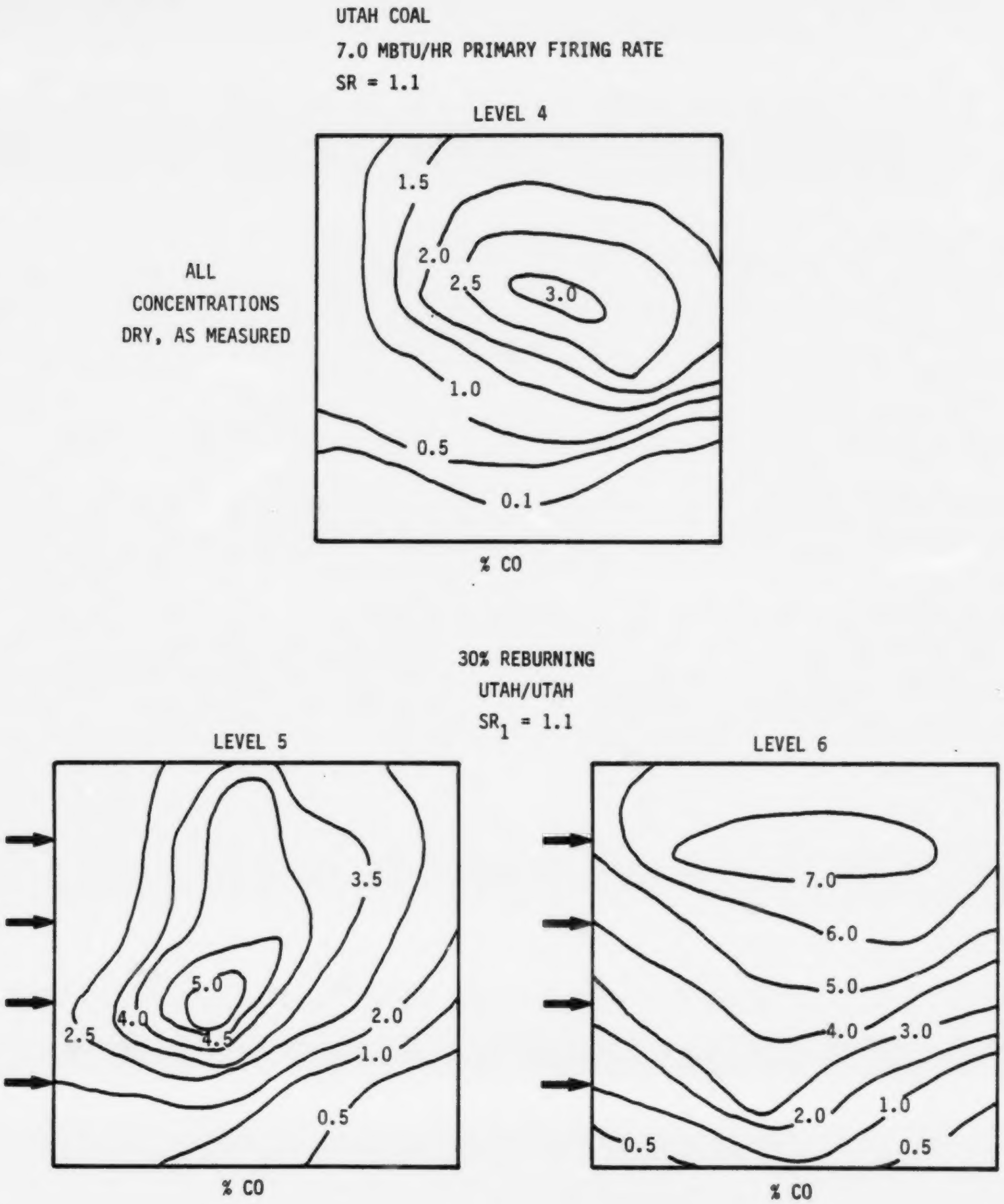


Figure 5-25. Reburning zone CO map.

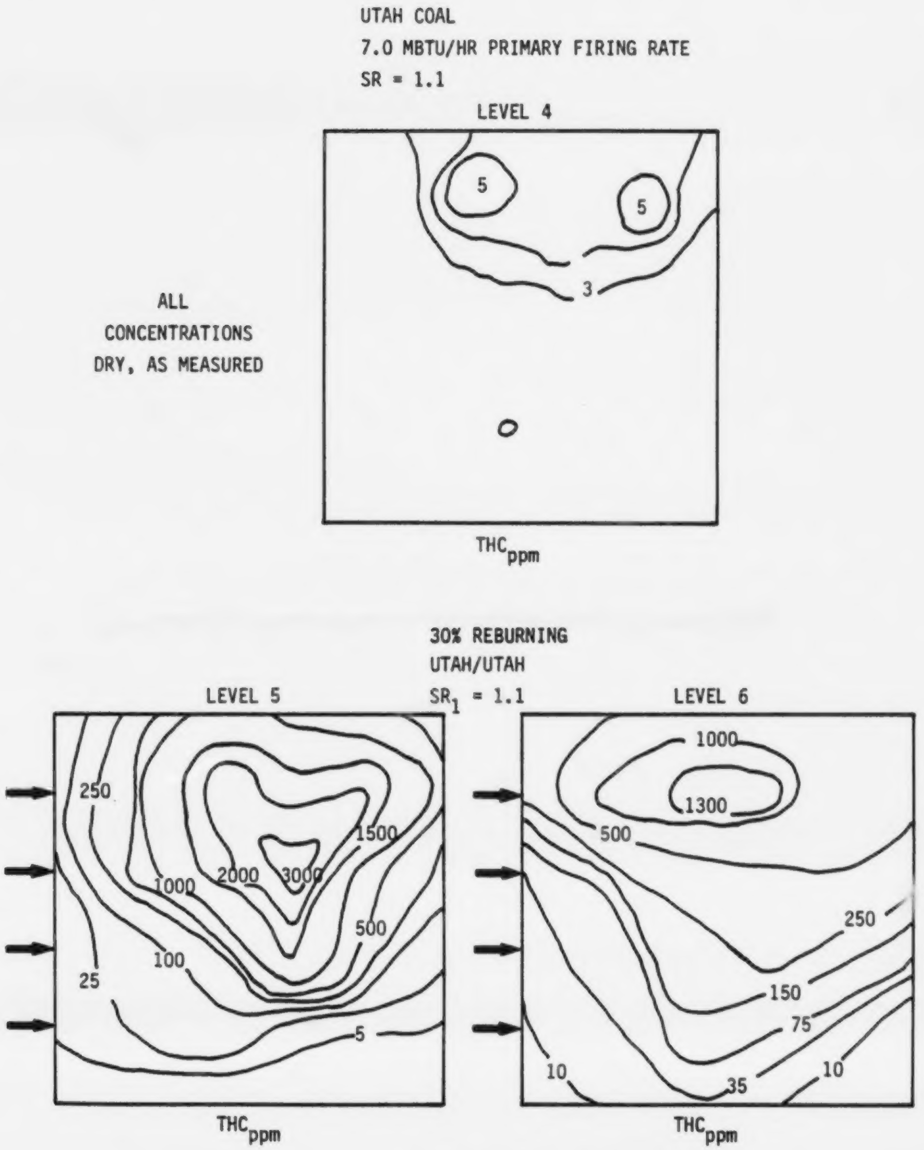


Figure 5-26. Reburning zone THC map.

schemes did show slightly better reduction than others. For the burnout air injection, there was no effect due to configuration. For reburning fuel injection, it appears that for most applications, better or faster mixing will result in lower emissions than slow mixing. This effectively allows more time in the fuel-rich zone for NO_x species to decay. The data also indicates that a high degree of jet penetration is necessary to increase reburning effectiveness. Stoichiometric parameters such as SR_r and SR_2 should also be taken in account to design a reburning system for a pilot or larger scale unit.

6.0 PROCESS OPTIMIZATION

For application of reburning to a full scale facility, baseline conditions employed on the pilot scale Reburning Tower may not be appropriate for the system involved. Several operating variables were investigated so that the reburning process can be optimized for a variety of operating conditions. The use of air as the reburning fuel transport medium was explored, as well as studies on the impacts of primary fuel (including primary zone burnout and primary NO_x) and reburning fuel on NO_x emissions.

6.1 Air as Reburning Fuel Transport Medium

The results obtained when air was used as transport medium are shown in Figure 6-1. Utilization of air as the carrier gas caused substantial increase in reburning transport line stoichiometries (SR_r). The premixing of oxygen with the reburning fuel was previously found to be detrimental to the reburning process (See Chapter 4.0). With excess primary zone air and twenty percent reburning fuel, it was not possible to achieve a substoichiometric amount of air in the reburning zone, so the process was intrinsically not "reburning". A further decrease in the air flowrate to obtain a fuel rich zone would have led to problems with coal dropout due to an insufficient carrying velocity. The trend of the data indicated that NO_x emissions tended to decrease as air flowrates, hence SR_r and SR_2, decreased, then leveled off at lower flows as any further benefit from lower stoichiometries was negated by inadequate mixing.

The NO_x emissions obtained when a stoichiometric amount of primary zone air was employed, shown in Figure 6-2, exhibited a similar trend at low air flowrates. The decrease in primary zone air created a fuel-rich reburning zone, but the nonoptimal SR_2 and high SR_r hindered efficient reduction of NO_x, and resulted in emissions much higher than those obtained with FGR as the transport medium.

The CO emissions with air and FGR as transport medium are shown in Figure 6-3. The lower CO levels found when air was used imply that carbon

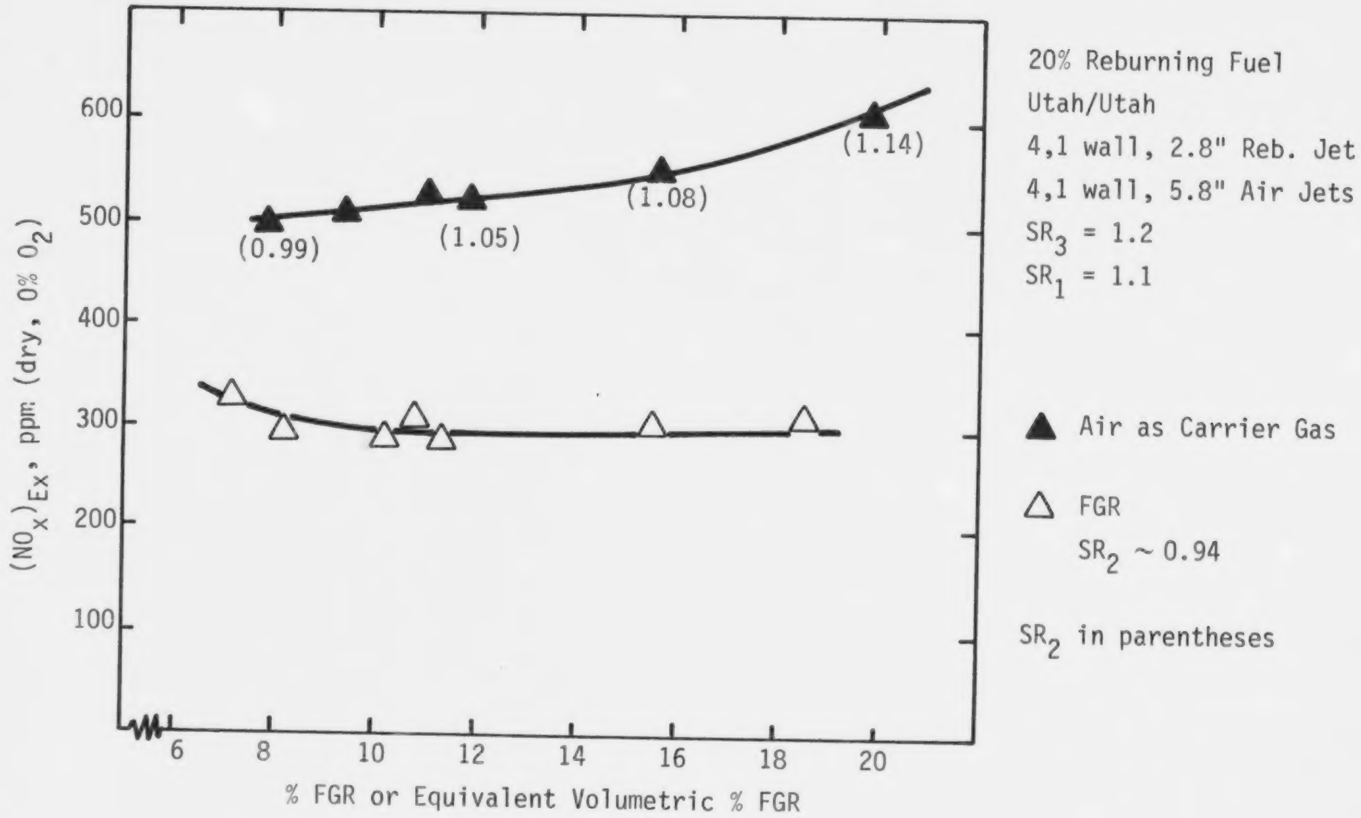


Figure 6-1. Influence of reburning fuel transport medium on NO$_x$ emissions.

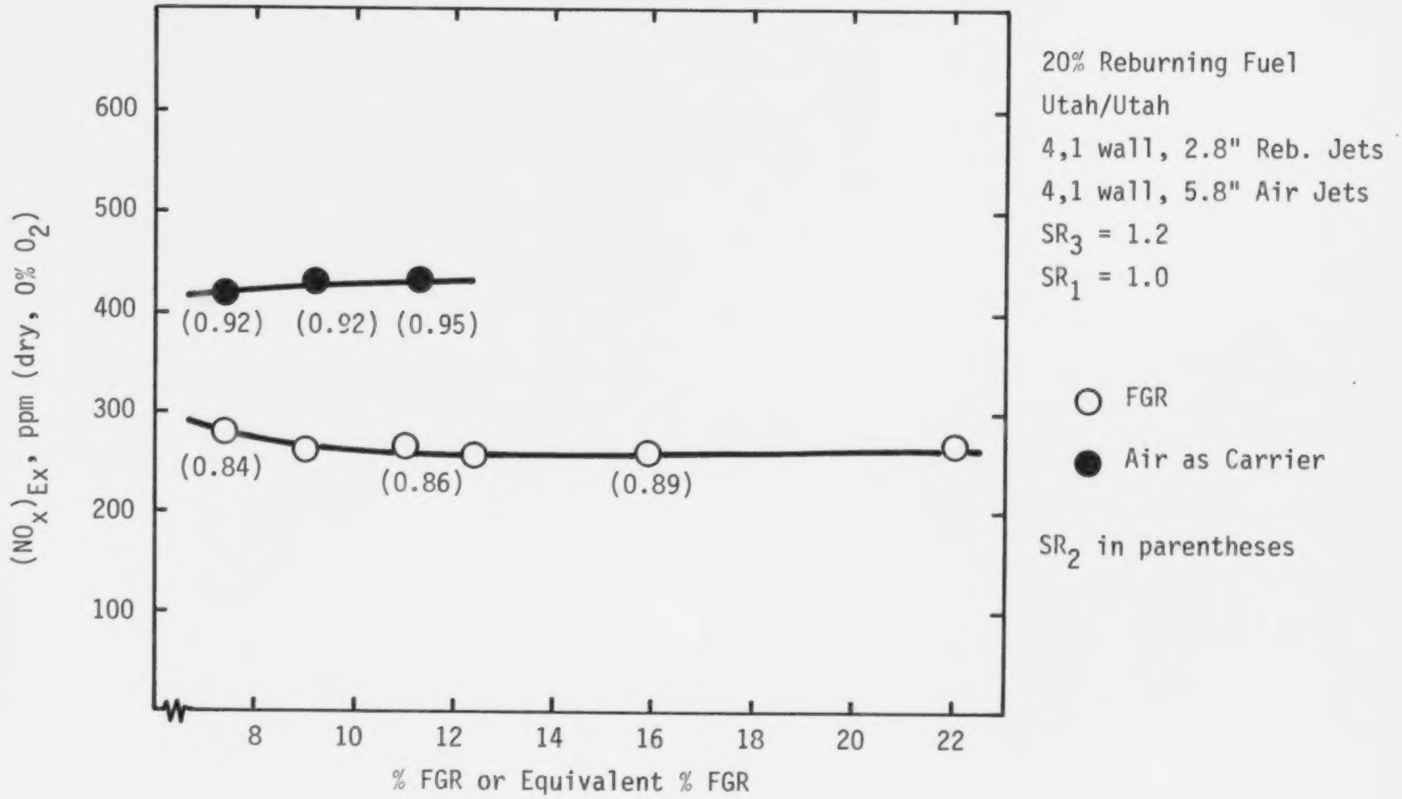


Figure 6-2. Transport medium effect at low primary zone stoichiometry.

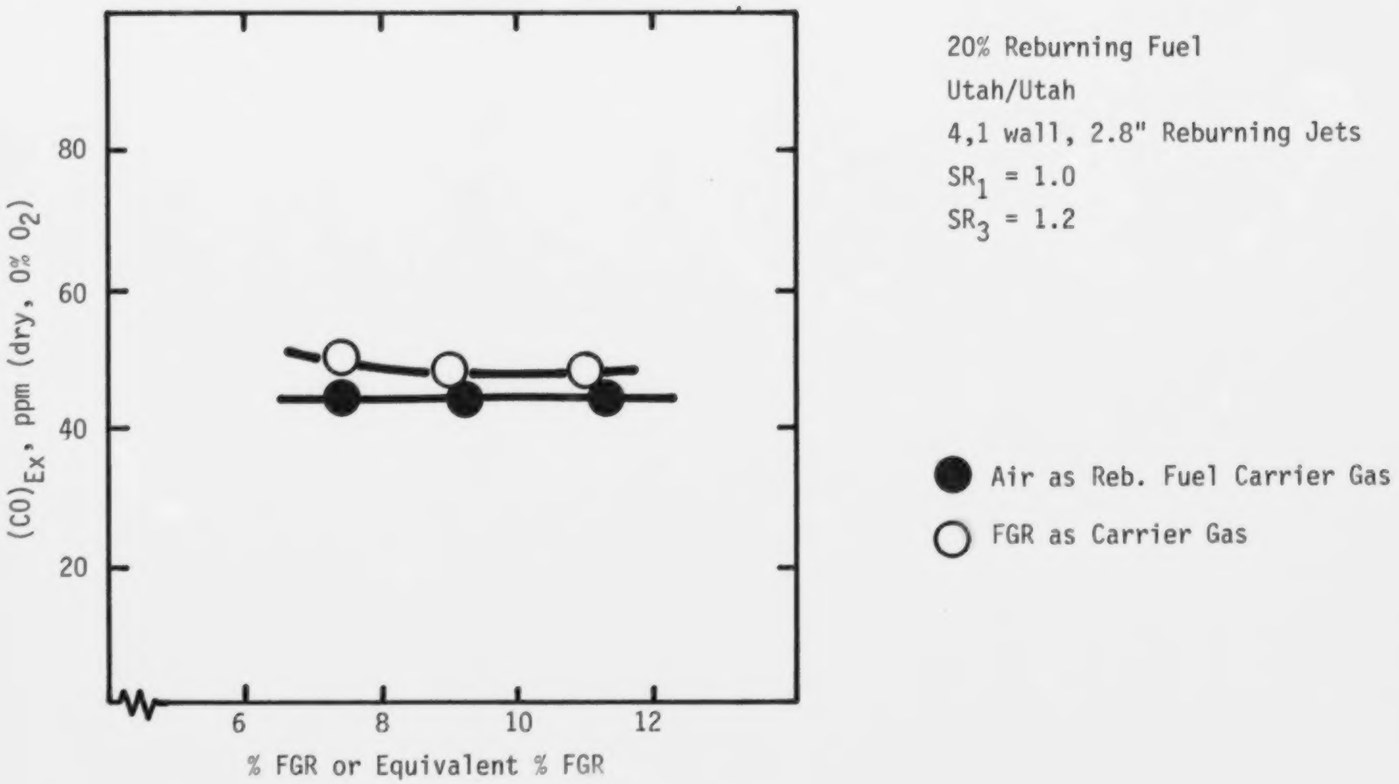


Figure 6-3. Influence of reburning fuel transport medium on CO emissions.

burnout was more complete, but the differences between the two transport mediums was not substantial.

Tests were completed with thirty percent reburning fuel to furnish lower transport line and reburning zone stoichiometries. Figure 6-4 compares results obtained at two different injection configurations for each fuel ratio. No difference was seen between the configurations at twenty percent reburning. Since a fuel-rich zone was not attained for this case, NO reduction did not occur, thus reburning fuel mixing was unimportant.

With thirty percent reburning, a substantial decrease in SR_r and SR_2 occurred, and reduction of NO_x was observed. Conversely to results obtained with FGR at twenty percent reburning, one large reburning jet offered lower NO_x emissions than four wall-fired jets with the difference between the two magnified at higher air flowrates. The greater deviation between the configurations at a higher SR_r suggest that premixing of oxygen with the fuel was more complete in four jets, and as oxygen levels rose, the enhanced NO_x formation characteristic of premixed burners became more pronounced.

If the amount of reburning fuel was increased such that reburning zone stoichiometries were similar, NO_x emissions obtained with air approached levels seen with FGR as transport medium, as shown in Figure 6-5. Results presented in Figure 6-6 indicate that when the reburning zone was made more fuel-rich, NO_x reduction with air as transport can match that of FGR. The SR_2 obtained with FGR was lower than the optimum for reburning, so the detrimental effect of a higher SR_r for the air system was overcome.

In summary, for application of the reburning process when air must be used as the transport medium, a larger amount of fuel must be injected in the reburning zone, with thirty percent suggested. Air flowrates should be limited and the primary zone stoichiometry as low as possible so that SR_r effects are limited and a fuel-rich reburning zone attained.

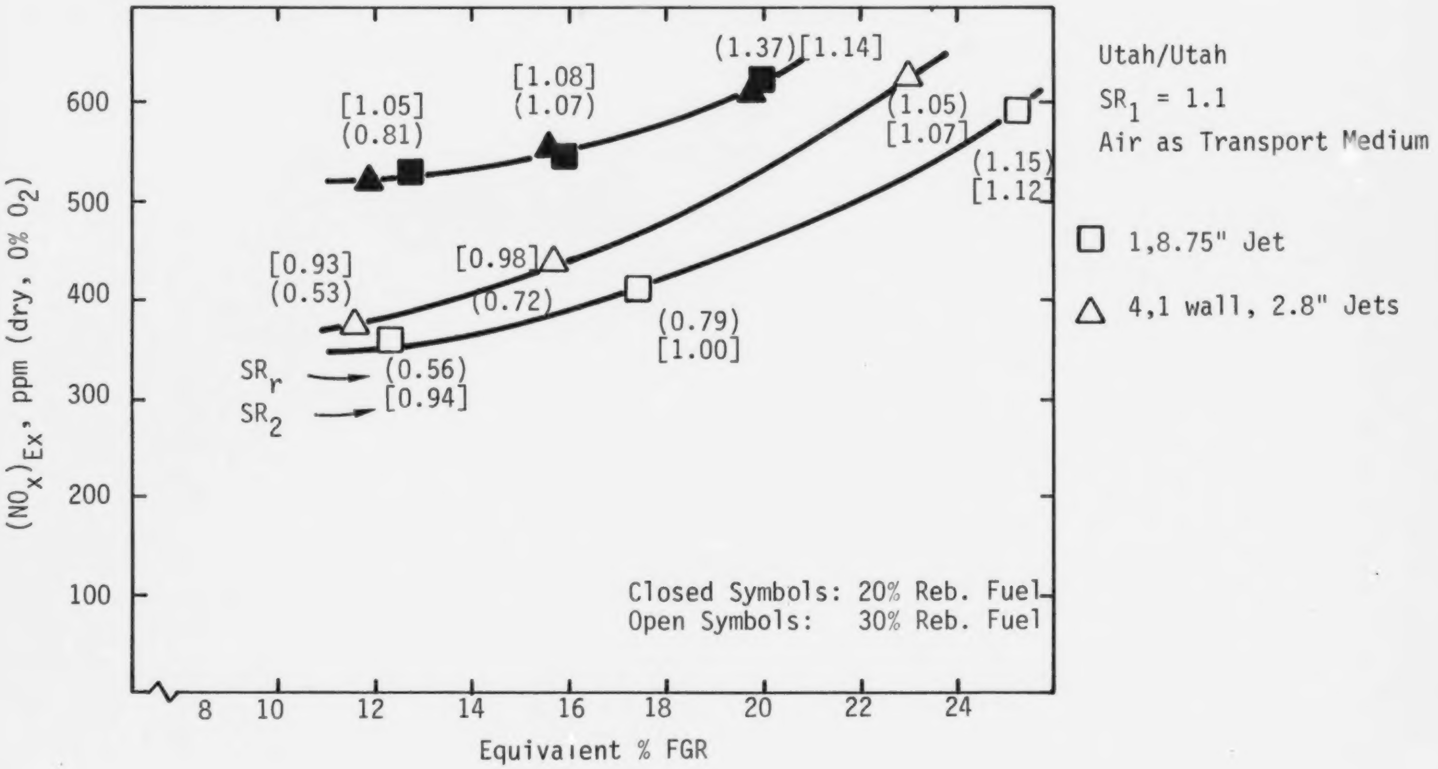


Figure 6-4. Influence of reburning fuel ratio and injection configuration on NO_x emissions.

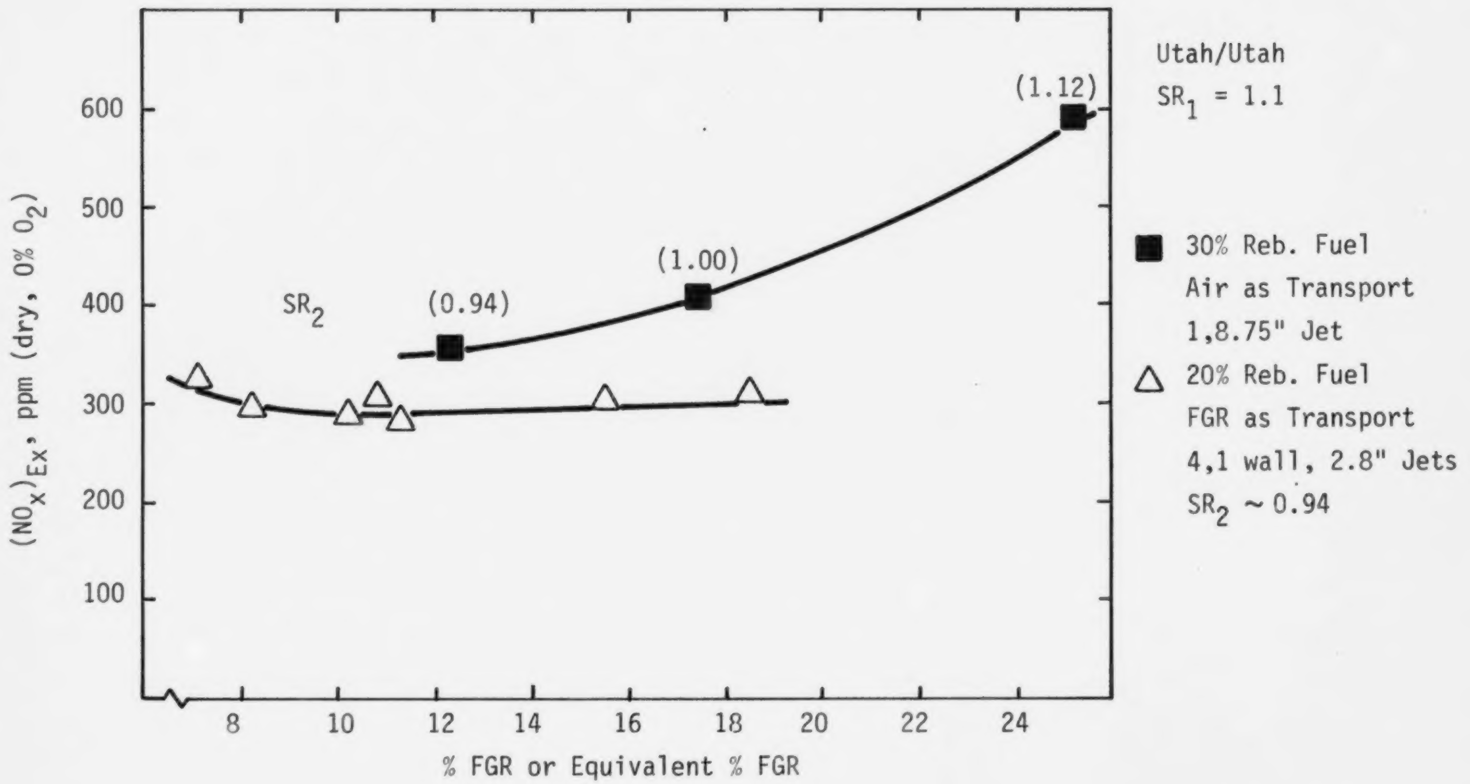


Figure 6-5. Comparison of air vs FGR as transport medium at similar SR_2.

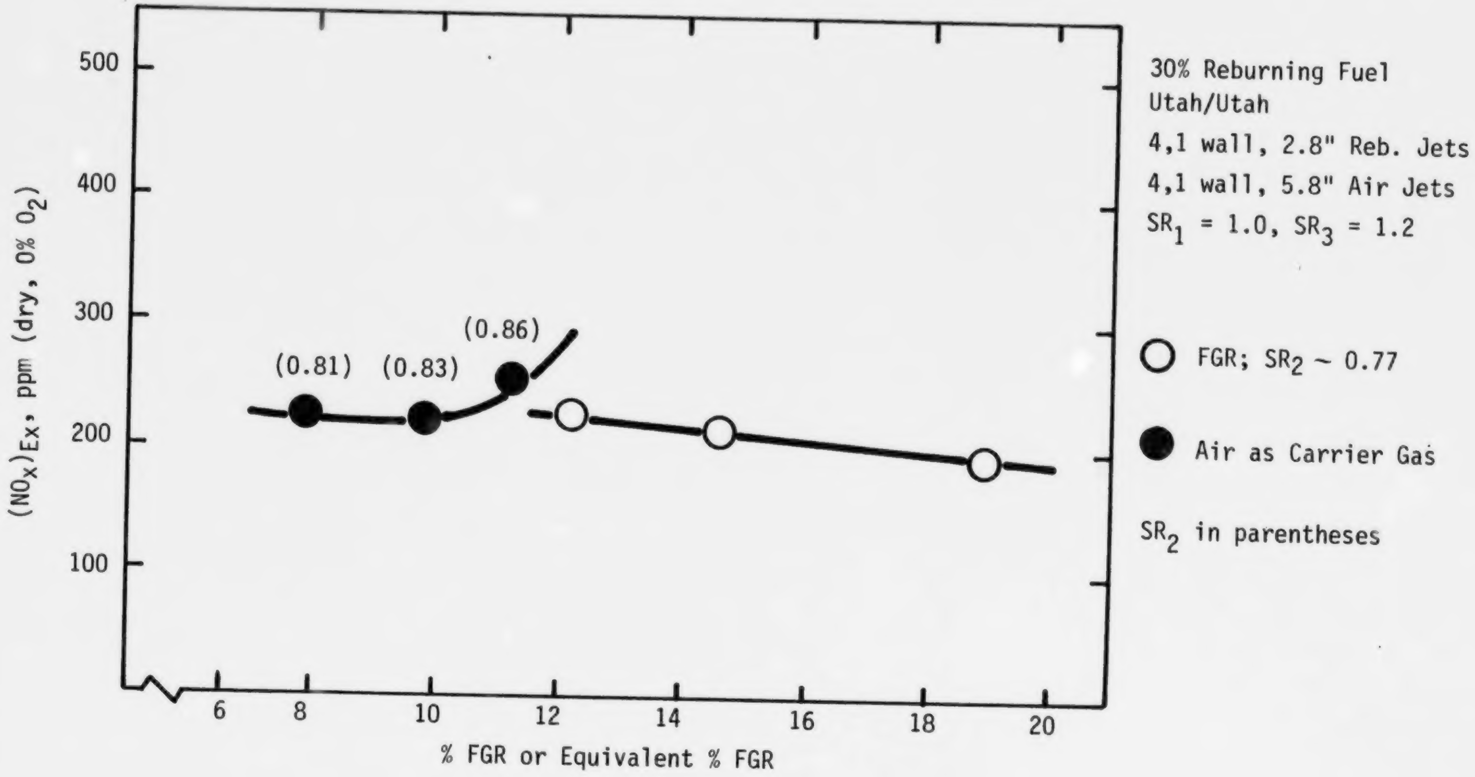


Figure 6-6. Air vs. FGR as transport medium at low SR_2.

6.2 Primary Fuel Effects

Tests were completed with natural gas as the primary fuel so that the effects of primary zone burnout and primary NO_x on the reburning process could be determined. The location for primary zone exit samples is shown in Figure 2-2. The uncontrolled NO_x emissions for natural gas is compared to that of Utah coal in Figure 6-7. For investigation of primary NO_x effects, levels of NO_x were increased up to 1000 ppm via addition of ammonia to the main burner secondary air. Measurements taken at the primary zone exit and exhaust, shown in Figure 6-8, showed that thorough ammonia oxidation occurred prior to the primary zone exit.

6.2.1 Primary Zone Burnout

Radial concentration and temperature profiles for the primary zone exit are displayed in Figure 6-9. Measurements were made from the furnace centerline to the wall. The composition gradients present when coal was the primary fuel were not seen for natural gas firing. The large deviation in CO measurements between the two fuels indicated that burnout was complete for radially injected natural gas while axial coal injection resulted in incomplete fuel burnout. When reburning was applied, more efficient NO_x reduction resulted when gas was the primary fuel, as shown in Figure 6-10. Although gas had higher levels of primary NO_x, the emissions after reburning were at least as low as those found when coal was the primary fuel. The ratio of exhaust to primary emissions for the two fuels indicated that the reburning process proceeded more efficiently when primary zone burnout was complete. Similar trends were observed in a bench scale study where a variety of primary fuels were tested with natural gas reburning (Seeker, et al., 1985).

6.2.2 Primary NO_x Concentration

The results of tests which investigated the impact of primary NO_x levels on emissions are shown in Figure 6-11, with percent NO_x reduction plotted in Figure 6-12. The data at stoichiometric and ten percent excess primary zone

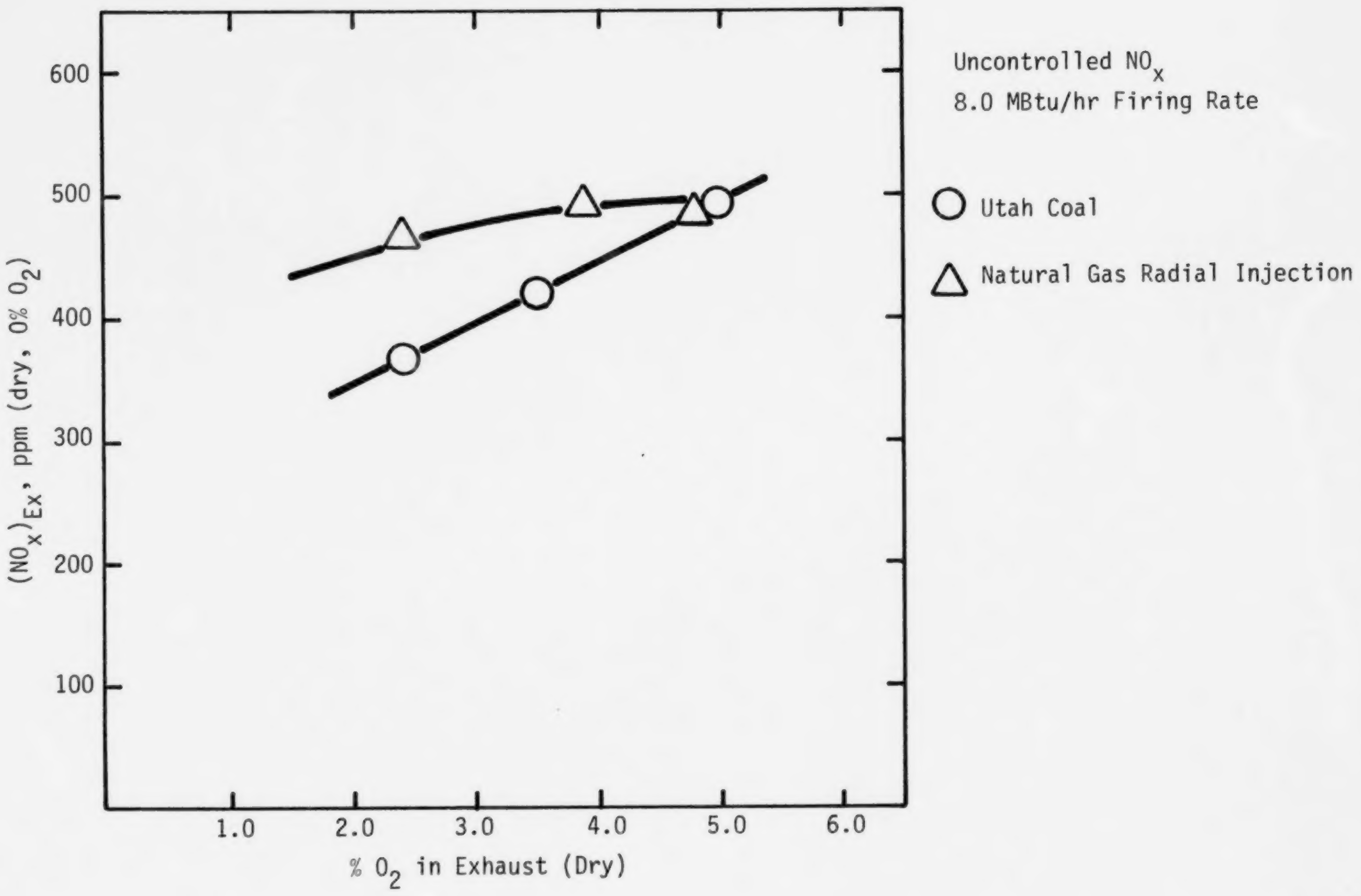


Figure 6-7. Uncontrolled NO_x emissions for natural gas and Utah coal.

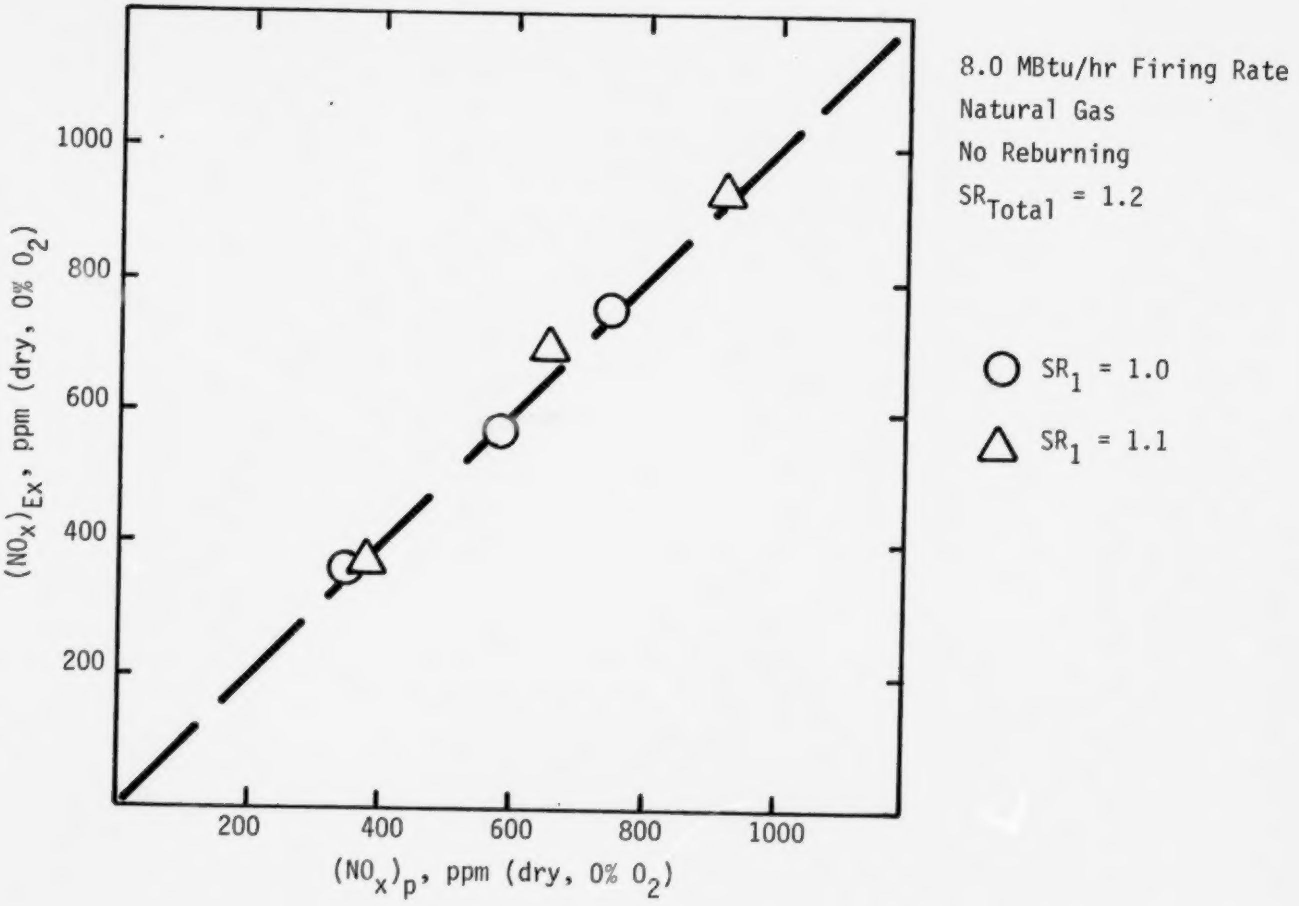


Figure 6-8. Investigation of primary zone ammonia burnout.

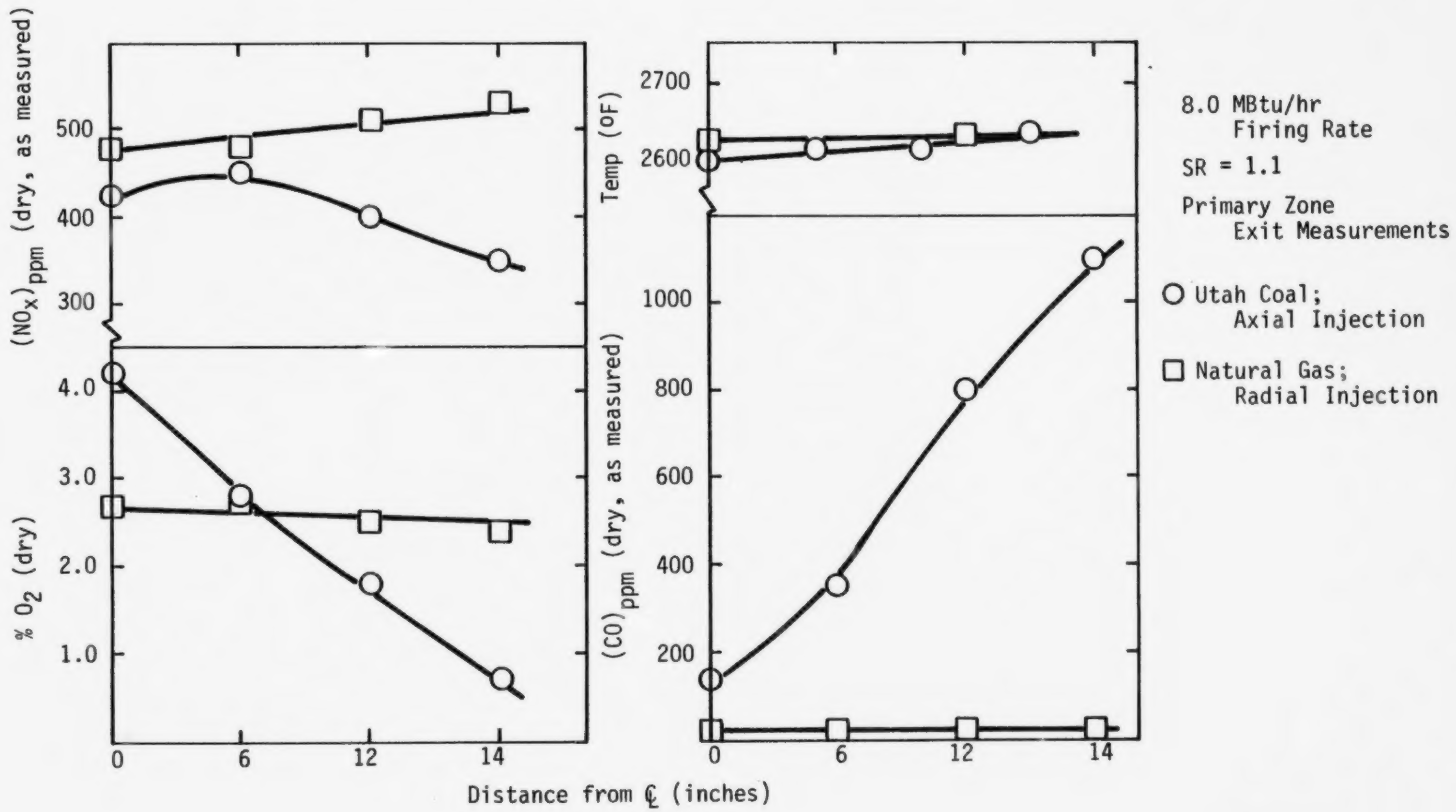


Figure 6-9. Primary zone exit composition and temperature profiles.

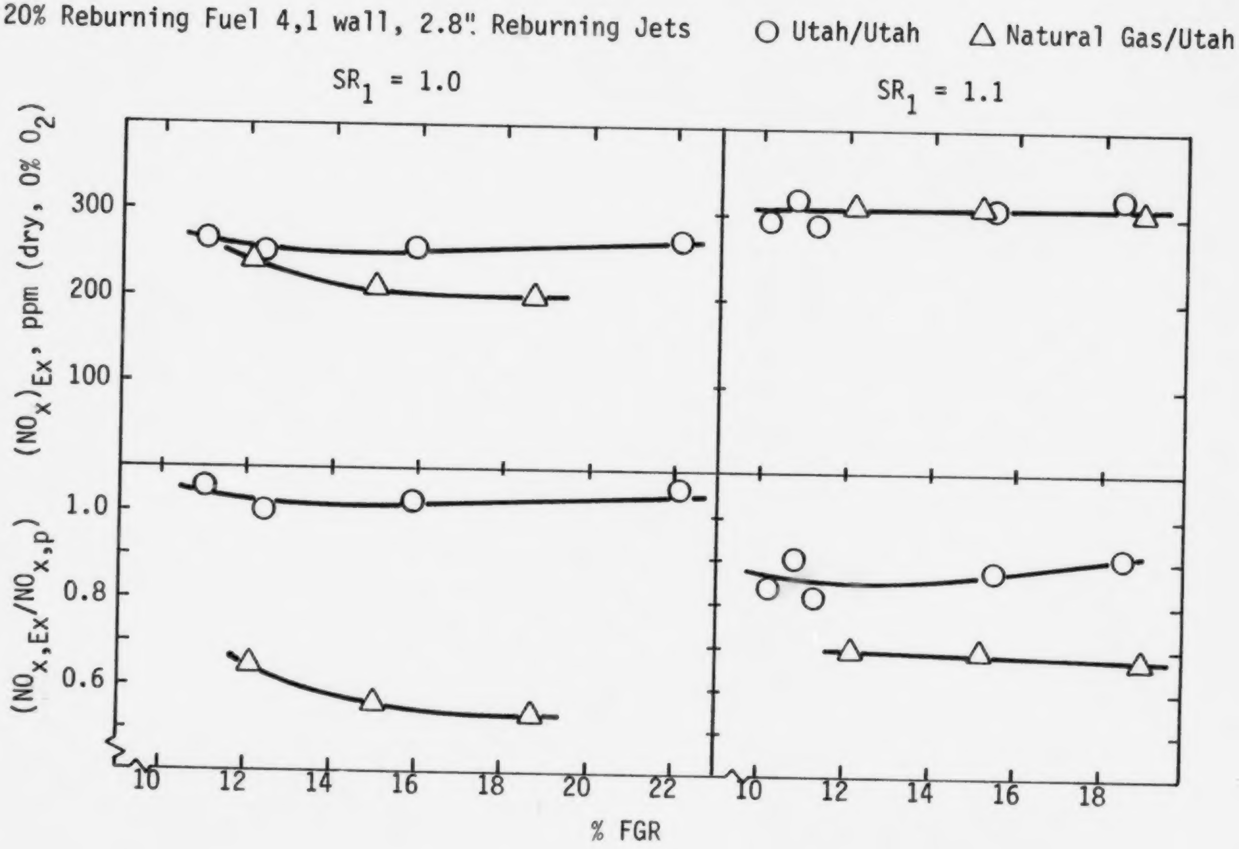


Figure 6-10. Influence of primary fuel on NO_x emissions.

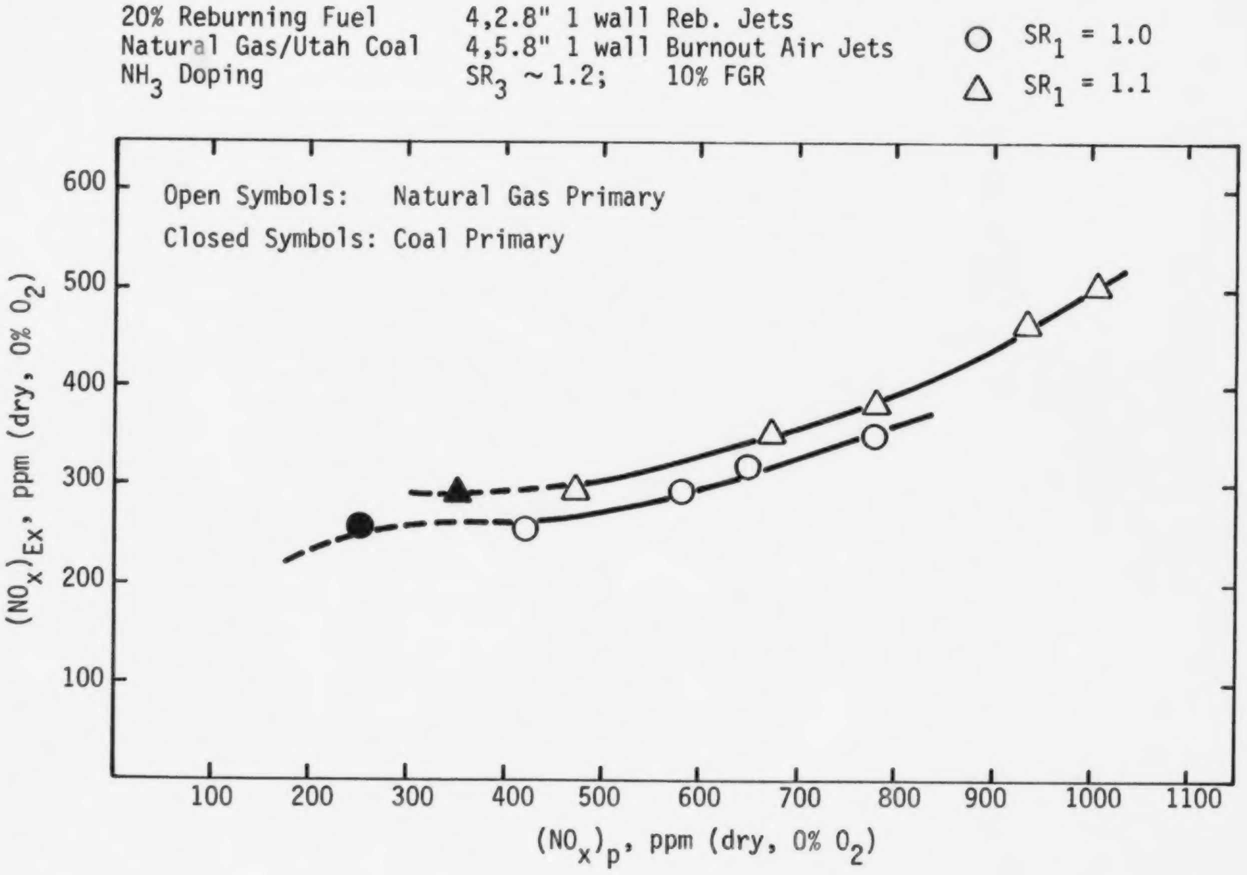


Figure 6-11. Influence of primary NO_x on emissions.

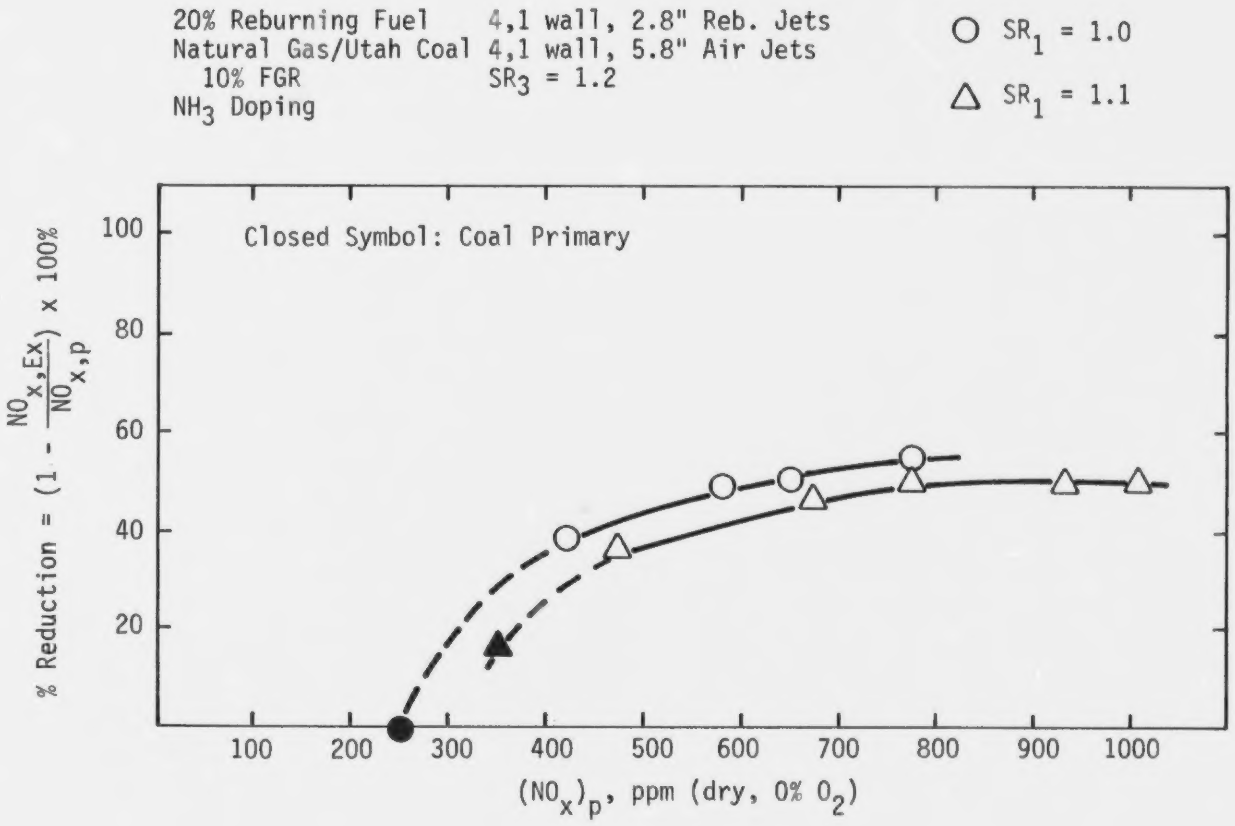


Figure 6-12. Influence of primary NO_x on NO_x reduction.

air parallel each other, with more efficient NO_x reduction obtained at the lower stoichiometry. Reduction capabilities of the reburning process increased with primary NO_x levels until the NO_x concentration reached about 800 ppm. Hence, a maximum reduction efficiency existed. This effect could likely be attributed to reaction kinetics of the NO reduction process. The coal points shown once again demonstrate the detrimental effect incomplete primary zone burnout imposes on the reburning process.

The burnout air was moved to level seven so that reburning zone residence time effects could be explored over a wide range of primary NO_x. The data, presented in Figure 6-13, followed a similar trend at both residence times. The increased time in the fuel-rich zone induced a greater reduction in emissions, as shown in Figure 6-14. In applications to full scale boilers, the benefits of lower NO_x emissions must be weighed against the harm caused by fuel-rich zone slagging when the reburning zone length is chosen.

The effect of furnace temperature at the reburning zone entrance was studied by moving the injection locations to levels five and seven for the reburning fuel and burnout air respectively. The results, illustrated in Figure 6-15 indicate no difference in reduction capabilities for the two cases. However, the reburning zone residence time for the lower injection temperature case was about fifteen percent longer due to differences in the reburning zone length and temperature. Therefore, it is likely that if identical residence times were used for each system, a hotter injection temperature would yield lower emissions. This effect could be attributed to reburning zone reaction kinetics.

Primary NO_x effects were also investigated at thirty percent reburning, with air as the reburning fuel transport medium. Exhaust emissions and percent reduction are presented in Figures 6-16 and 6-17, respectively. The data follows the same trend as data at twenty percent reburning, with lower emissions and better reduction at a lower primary zone stoichiometry. A comparison of primary NO_x effects for twenty and thirty percent reburning is

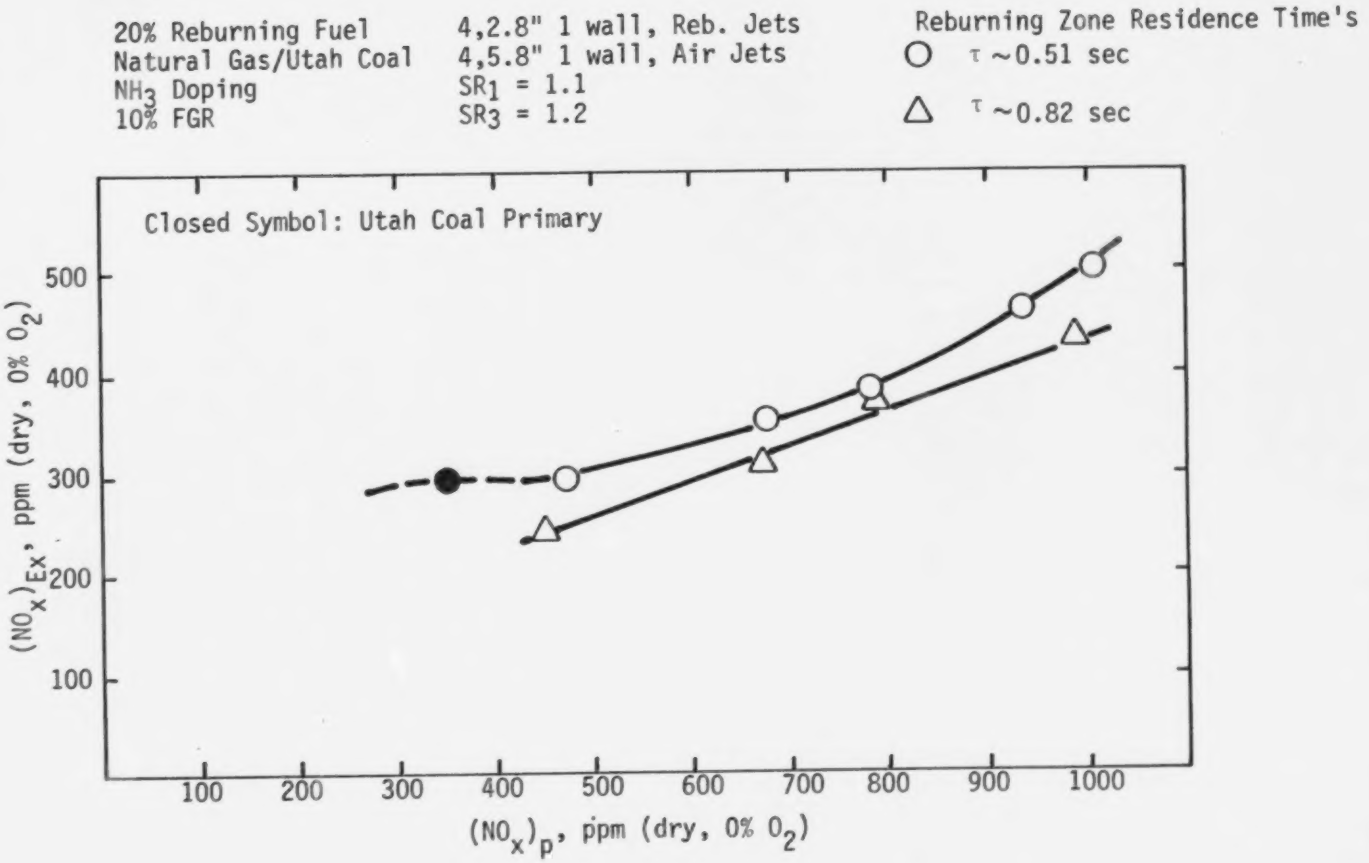


Figure 6-13. Influence of reburning zone residence time on exhaust NO_x.

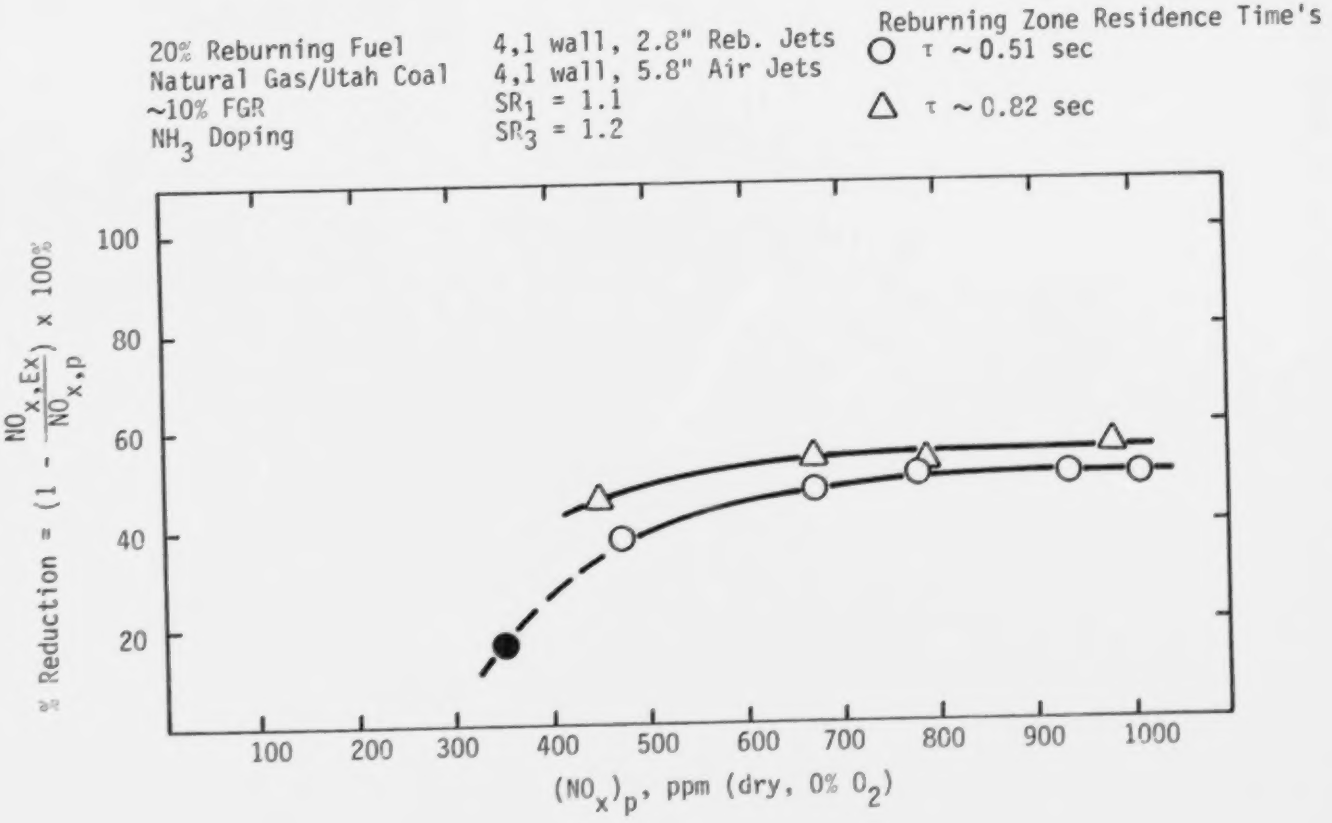


Figure 6-14. Residence time effect on NO_x reduction.

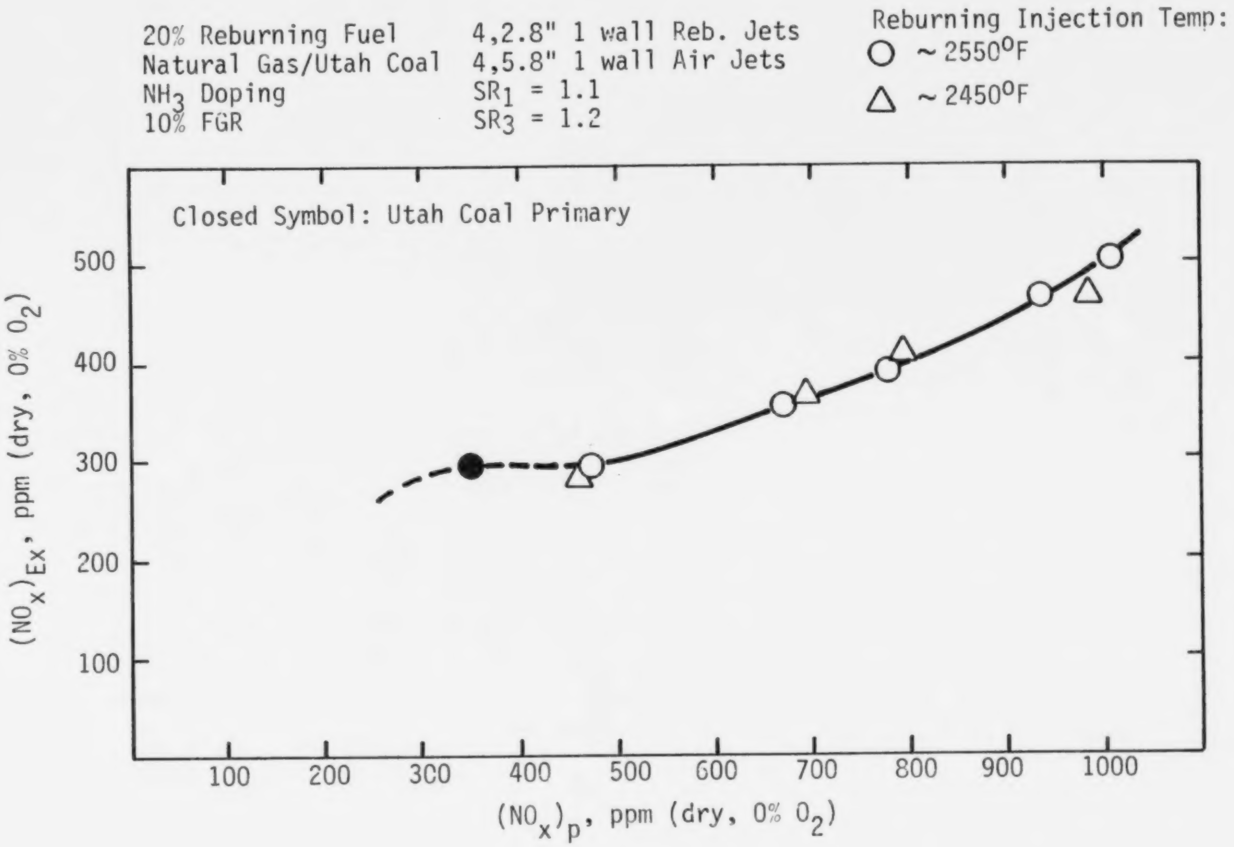


Figure 6-15. Influence of reburning zone temperature on NO_x emissions.

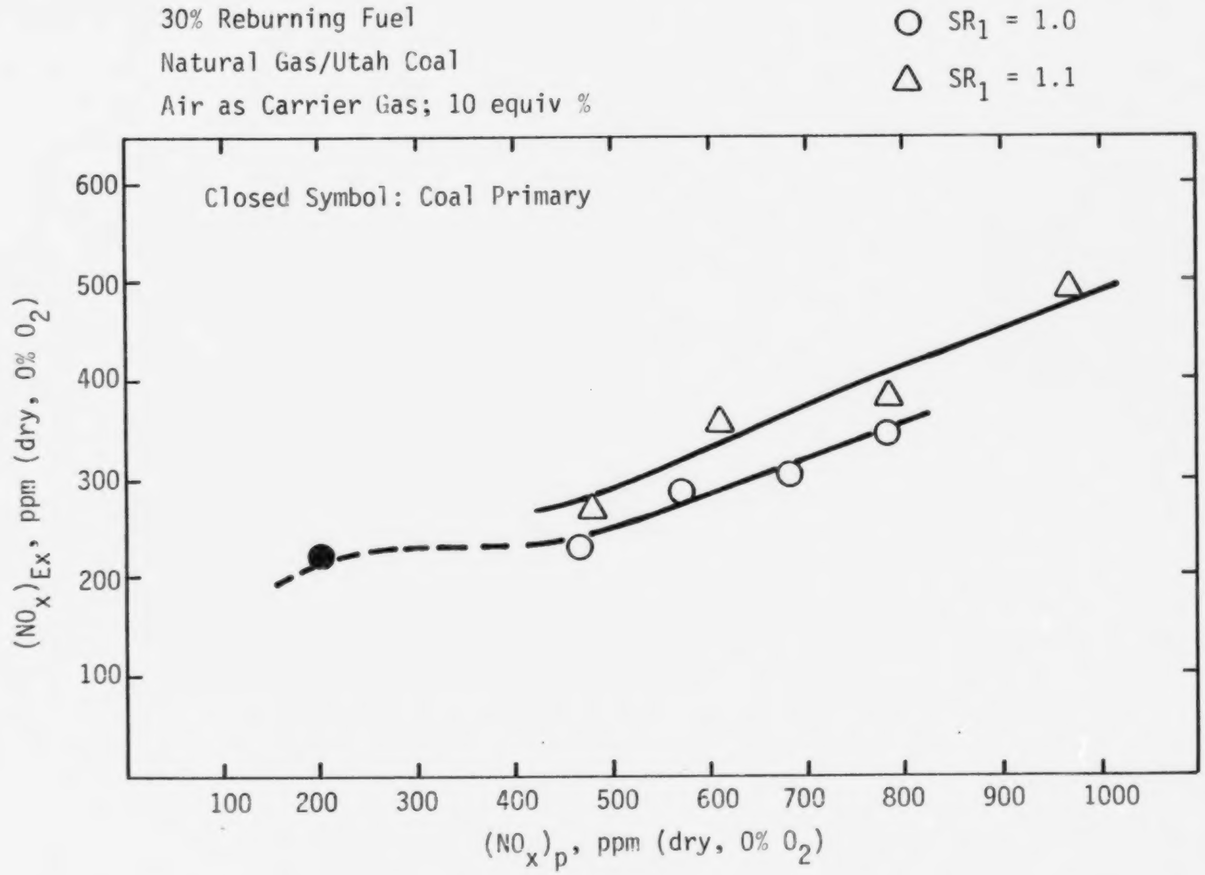


Figure 6-16. Primary NO_x effect at high reburning fuel ratio.

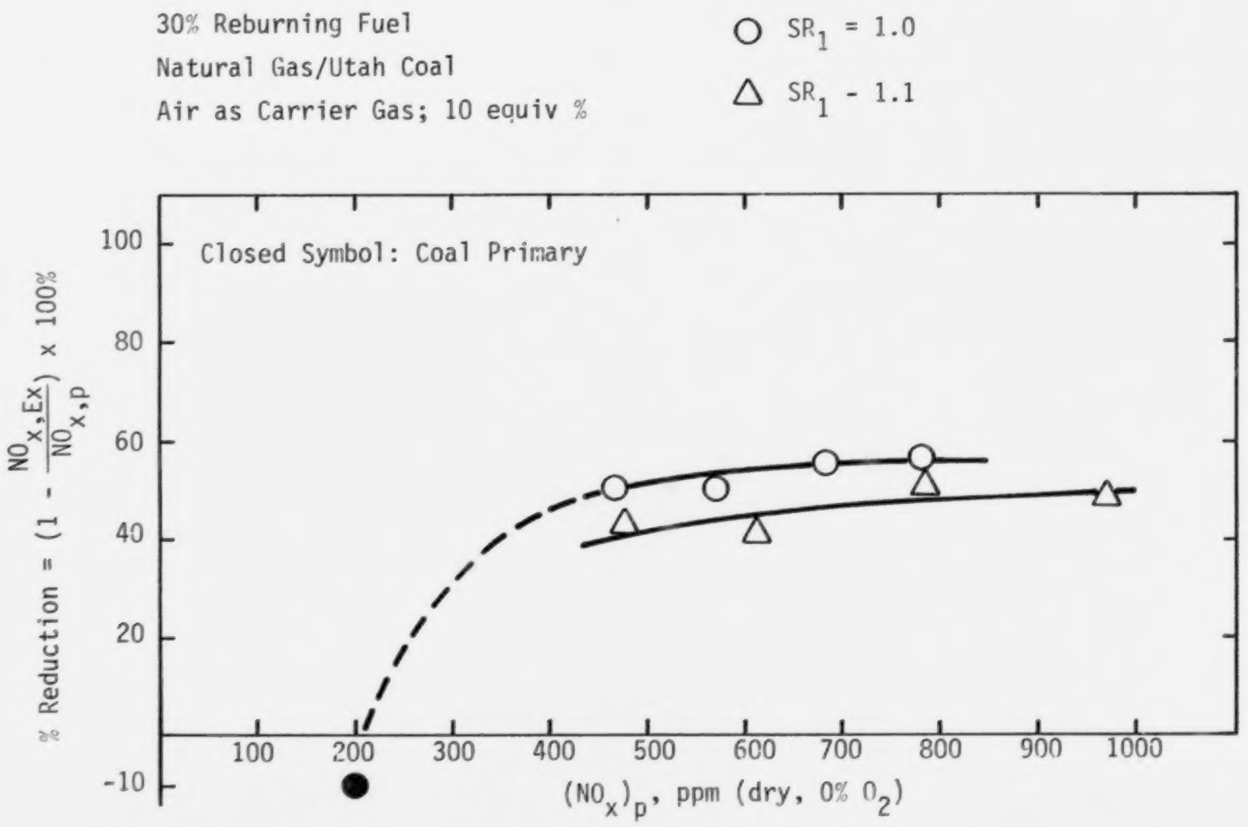


Figure 6-17. Percent NO_x reduction at high reburning fuel ratio.

shown in Figure 6-18. Little difference was seen between the two sets of data.

6.3 Natural Gas as Reburning Fuel

A comparison between natural gas and coal as reburning fuel on the bench scale CTT showed that gas reburning was more efficient than coal at equivalent firing rates (Seeker, et al., 1986). Based on this, tests were run with natural gas reburning on the pilot scale reburning tower. The gas was injected through four wall-fired jets designed to yield thorough jet penetration to ensure proper mixing. The results are shown in Figure 6-19. As expected, lower emissions resulted with natural gas. Several variables influenced this result. A variable of importance was the oxygen content of the reburning fuel stream. With natural gas as the fuel, no oxygen was added with the reburning fuel, thus a lower reburning zone stoichiometry was attained. A lack of transport line oxygen also removed any detrimental effect caused by SR_r. another advantage of natural gas is its lack of fuel-nitrogen. The fixed-nitrogen in coal which was available for oxidation to NO_x was not present in the natural gas. When NO_x emissions were plotted against SR_2, the difference in emissions between the two fuels diminished. This suggests that the oxygen effect was predominate when determining the advantages of gas reburning.

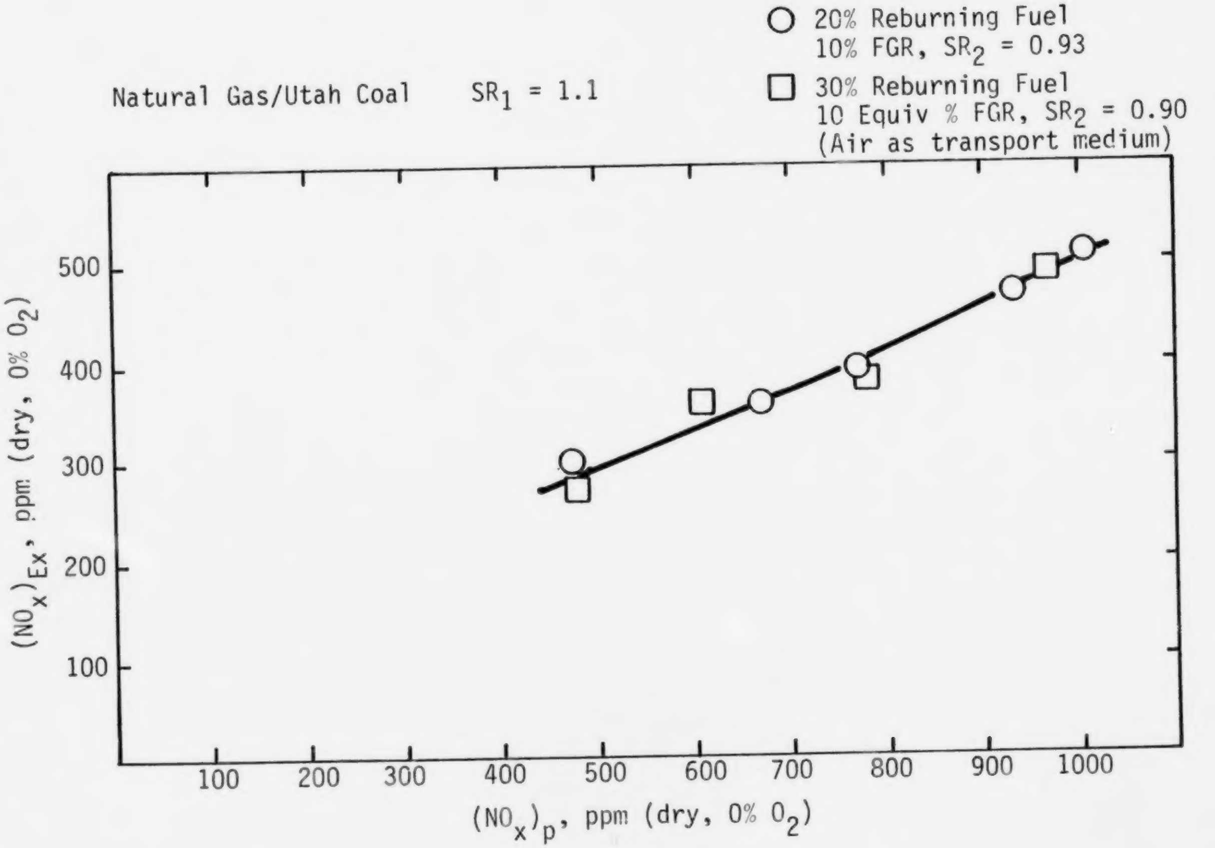


Figure 6-18. Comparison of primary NO_x effects for twenty and thirty percent reburning.

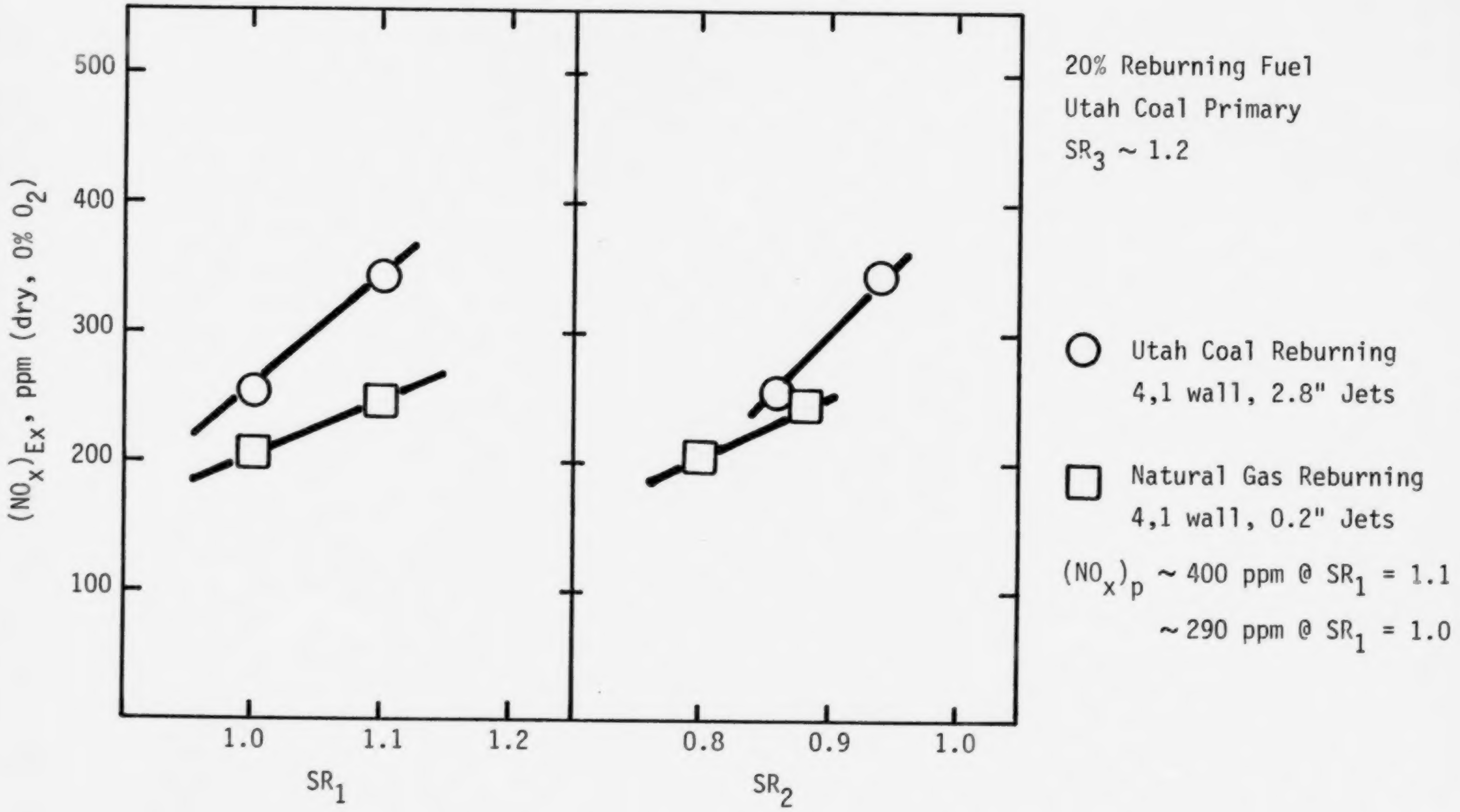


Figure 6-19. Comparison of natural gas and coal as reburning fuel.

7.0 COMBINED PROCESSES

Recent studies by Kawasaki Heavy Industries (Kato et al., 1982), Mitsubishi Heavy Industries (Takahashi et al., 1981), and Ishikawajima-Harima Heavy Industries (Miyamae, et al., 1985) of Japan have suggested that multiple-staged combustion techniques, which combine the standard reburning process with an additional reburning zone or staged combustion, are more effective in reducing NO_x emissions than standard reburning. The multiple reburning, or the Kawaski volume combustion (KVC) method, which employs two reburning zones, and the over-firing air plus reburning scheme,as adopted by MHI and IHI, were investigated on the Reburning Tower. Thirty percent reburning fuel was used, and the flowrates and injection configurations were chosen such that fuel-rich zone stoichiometries and mixing were optimal. A schematic of the two systems with the stoichiometries employed is illustrated in Figure 7-1. The air and fuel injection locations on the reburning tower are shown in Figure 7-2.

7.1 Multiple Reburning

For this process, the reburning fuel had to be split into two separate streams. Recirculated flue gas was the transport medium for the first stream, air for the second. In Figure 7-3, the NO_x emissions for two different splits of the reburning fuel are illustrated. The emissions were not dependent on the fuel split as long as the reburning zones were reasonable fuel rich. The NO_x emissions obtained with multiple reburning zones are compared to standard reburning emissions in Figure 7-4. The NO_x emissions were not strongly dependent on excess oxygen for either case, and although a larger percentage of the furnace operated under fuel-rich conditions for the multiple reburning process, NO_x emissions were only slightly lower.

As shown in Figure 7-5, CO emissions increased significantly when the overall stoichiometry was less than 1.2 (3.6 percent excess O_2). The lower emissions obtained with standard reburning suggested that carbon burnout increased when multiple reburning was applied. Due to the high amount of

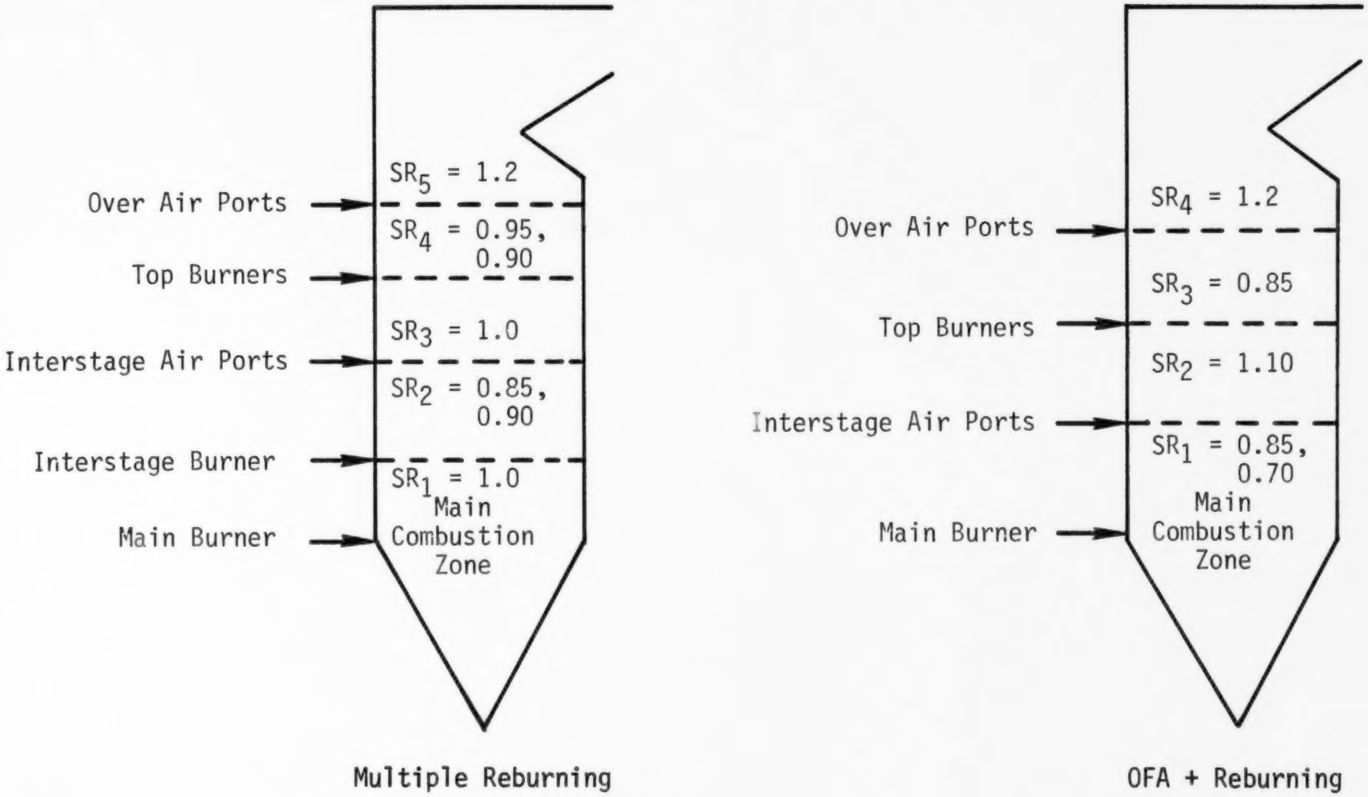
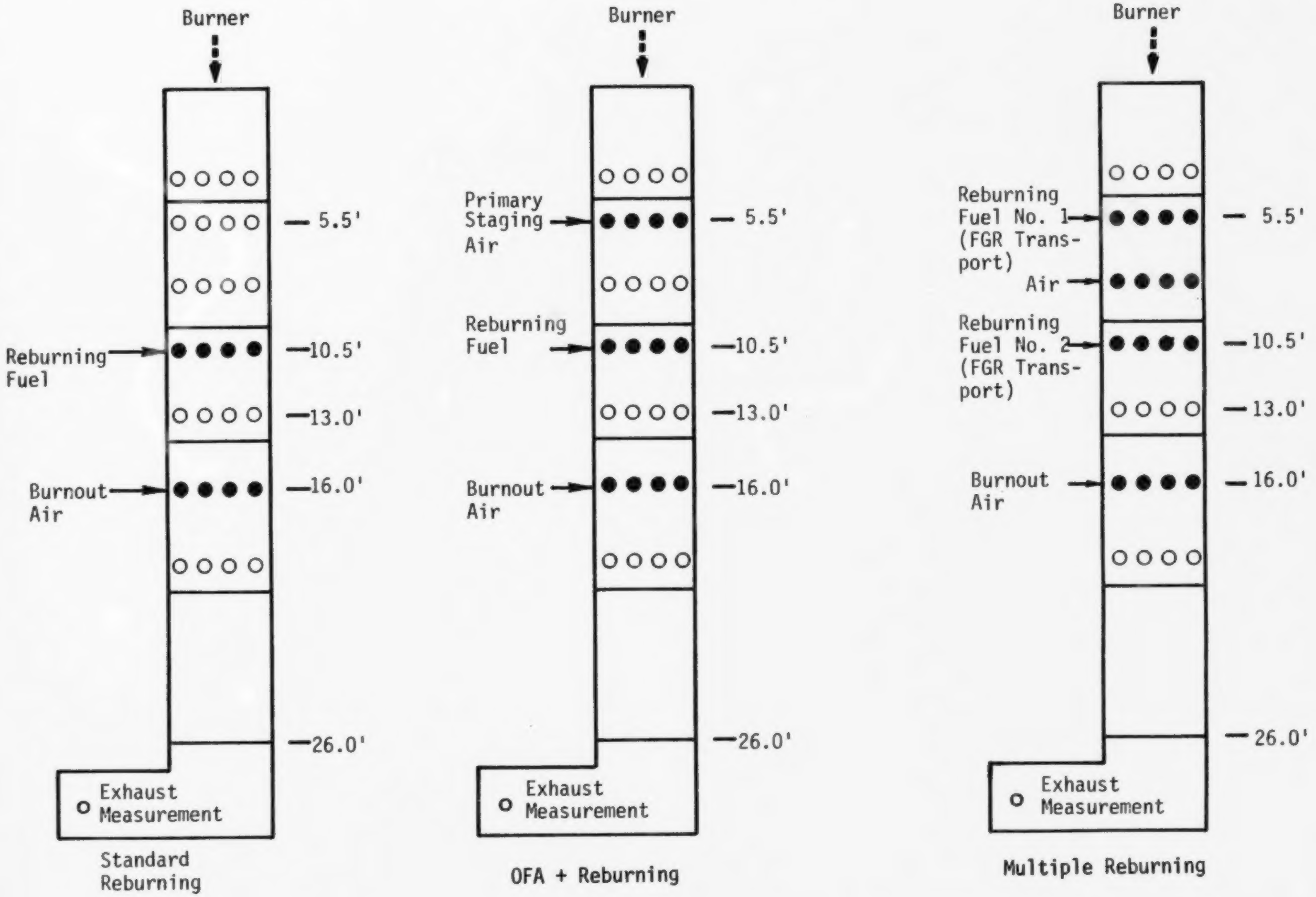

Over Air Ports
Top Burners
Interstage Air Ports
Interstage Burner
Main Burner
SR_5 = 1.2
SR_4 = 0.95, 0.90
SR_3 = 1.0
SR_2 = 0.85, 0.90
SR_1 = 1.0
Main Combustion Zone
Multiple Reburning
Over Air Ports
Top Burners
Interstage Air Ports
Main Burner
SR_4 = 1.2
SR_3 = 0.85
SR_2 = 1.10
SR_1 = 0.85, 0.70
Main Combustion Zone
OFA + Reburning

Figure 7-1. Multiple staged fuel/air injection schemes.


Burner
Reburning Fuel
Burnout Air
5.5'
10.5'
13.0'
16.0'
26.0'
Exhaust Measurement
Burner
Primary Staging Air
Reburning Fuel
Burnout Air
5.5'
10.5'
13.0'
16.0'
26.0'
Exhaust Measurement
Burner
Reburning Fuel No. 1 (FGR Transport)
Air
Reburning Fuel No. 2 (FGR Transport)
Burnout Air
5.5'
10.5'
13.0'
16.0'
26.0'
Exhaust Measurement

Standard Reburning

OFA + Reburning

Multiple Reburning

Figure 7-2. Injection locations for reburning processes.

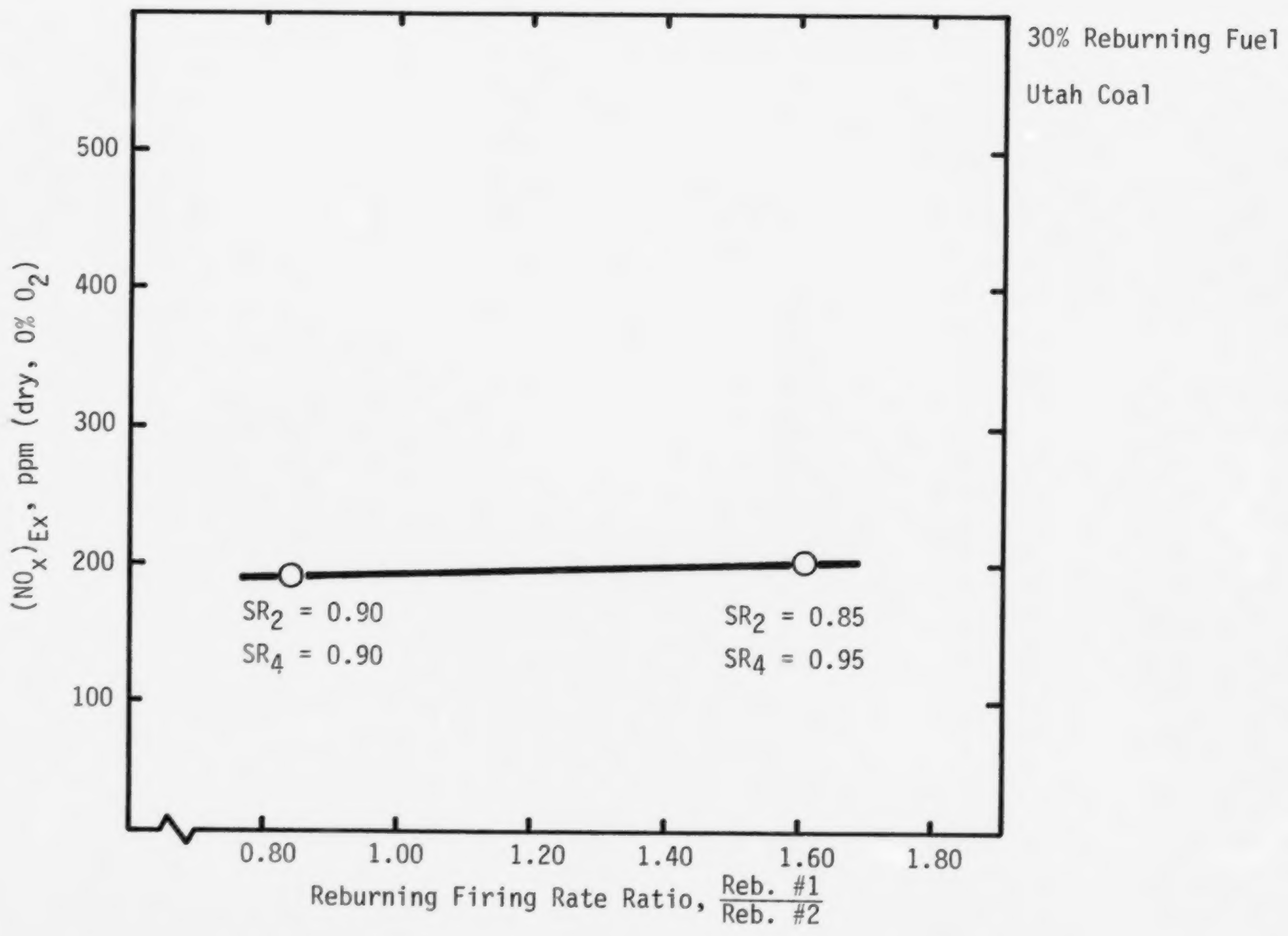


Figure 7-3. Influence of reburning fuel split on NO_x emissions for multiple reburning.

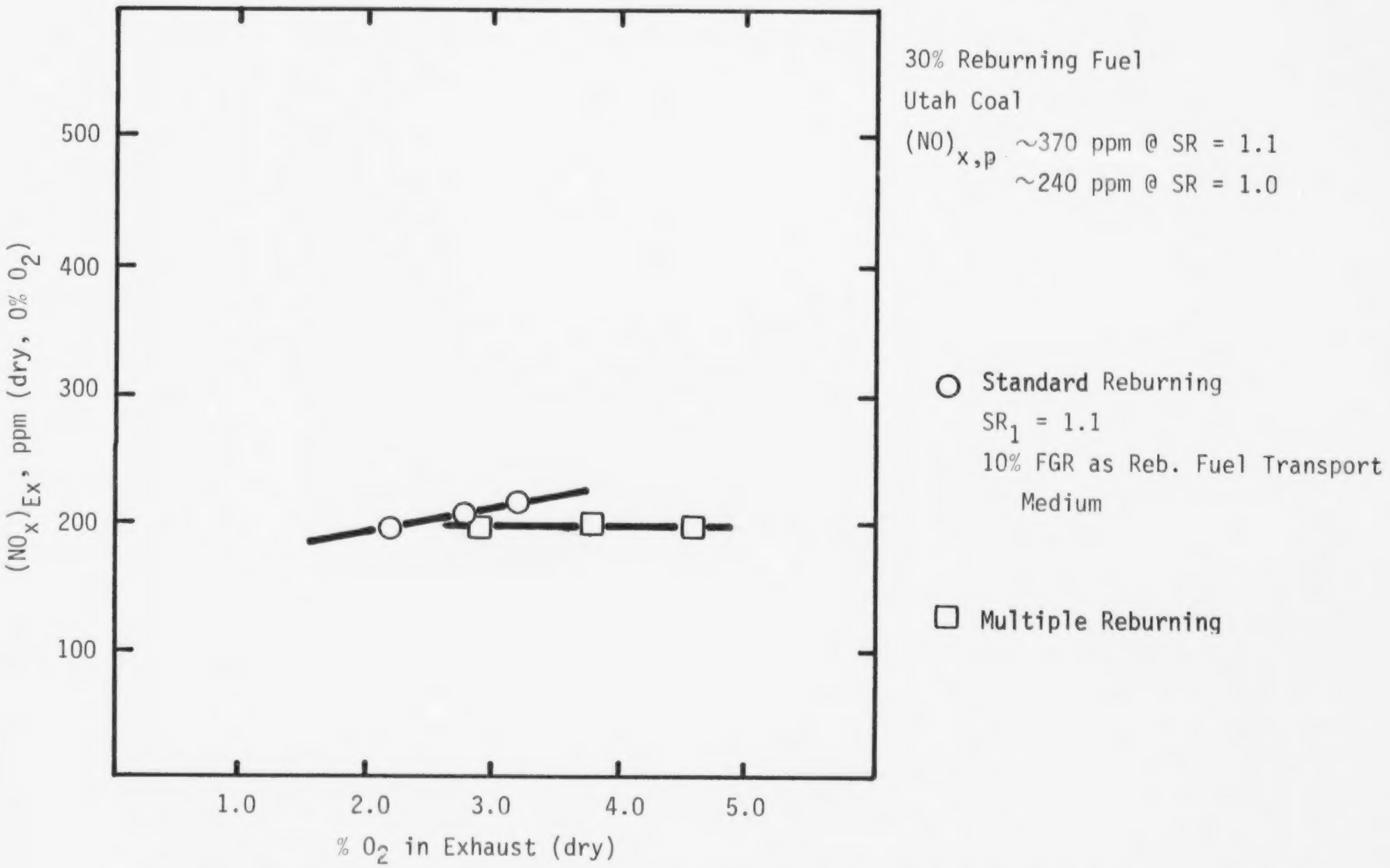


Figure 7-4. Comparison of NO_x emissions for standard and KVC reburning.

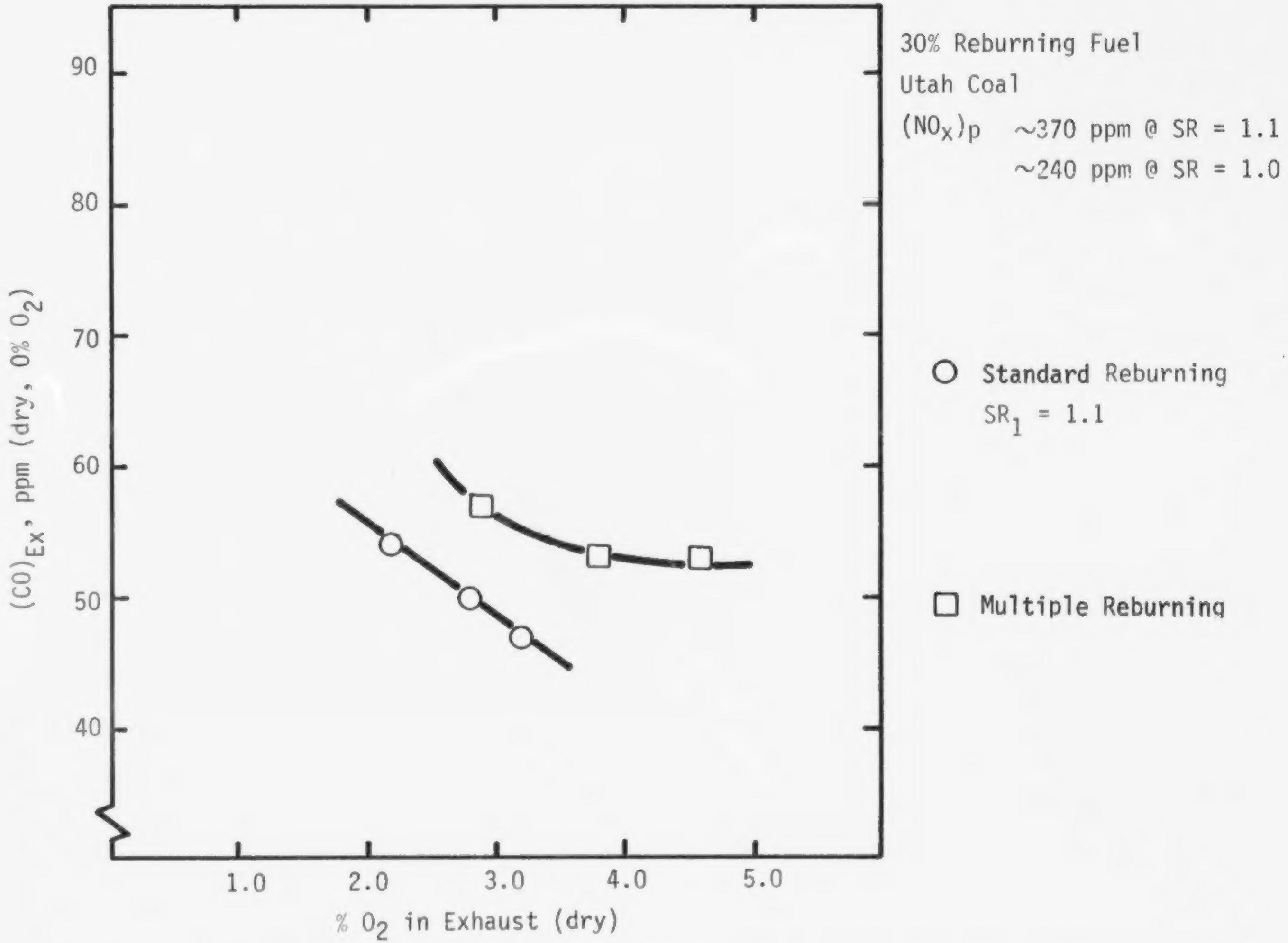


Figure 7-5. Comparison of CO emissions for standard and multiple reburning.

reburning fuel employed, and limitations of the system, the maximum overall stoichiometry attainable for standard reburning was slightly less than 1.2. Based on the multiple reburning results and data obtained at twenty percent reburning, it is likely that CO emissions would level off for the standard reburning case when excess O_2 exceeded 3.5 percent.

Since a larger percentage of the furnace operated under fuel-rich conditions with multiple reburning, the increased slagging and operational procedures incurred by this process diminish its feasibility for application to full scale boilers. Also, since a longer fuel-rich zone residence time enhances NO_x reduction (see Section 6.2.2), it is likely that a single reburning zone with a residence time similar to that of the total fuel-rich residence time in the KVC process would yield NO_x emissions at lease as low as those achieved with multiple reburning zones.

7.2 Over-Fire Air Plus Reburning

A comparison of NO_x emissions for standard reburning and staged combustion plus reburning are presented in Figure 7-6, with CO emissions compared in Figure 7-7. Once again, NO_x emissions were lower and CO emissions higher for the combined process. Similarly to the multiple reburning case, the lower NO_x emissions could be attributed to the longer fuel-rich zone present in the OFA plus reburning system, and a single, long reburning zone may surpass the reduction abilities of the combined process.

Presented in Figure 7-8 are the results obtained when the primary zone stoichiometry was varied. It has previously been shown that NO_x emissions are minimized when the fuel-rich zone stoichiometry is approximately 0.85 (Greene, et al., 1984; Overmoe, et al., 1985). A similar minimum was found for the OFA plus reburning process.

7.3 Combining with Sorbent Injection

The purpose of these tests was solely to get a handle on the capture levels that were possible under reburning conditions.

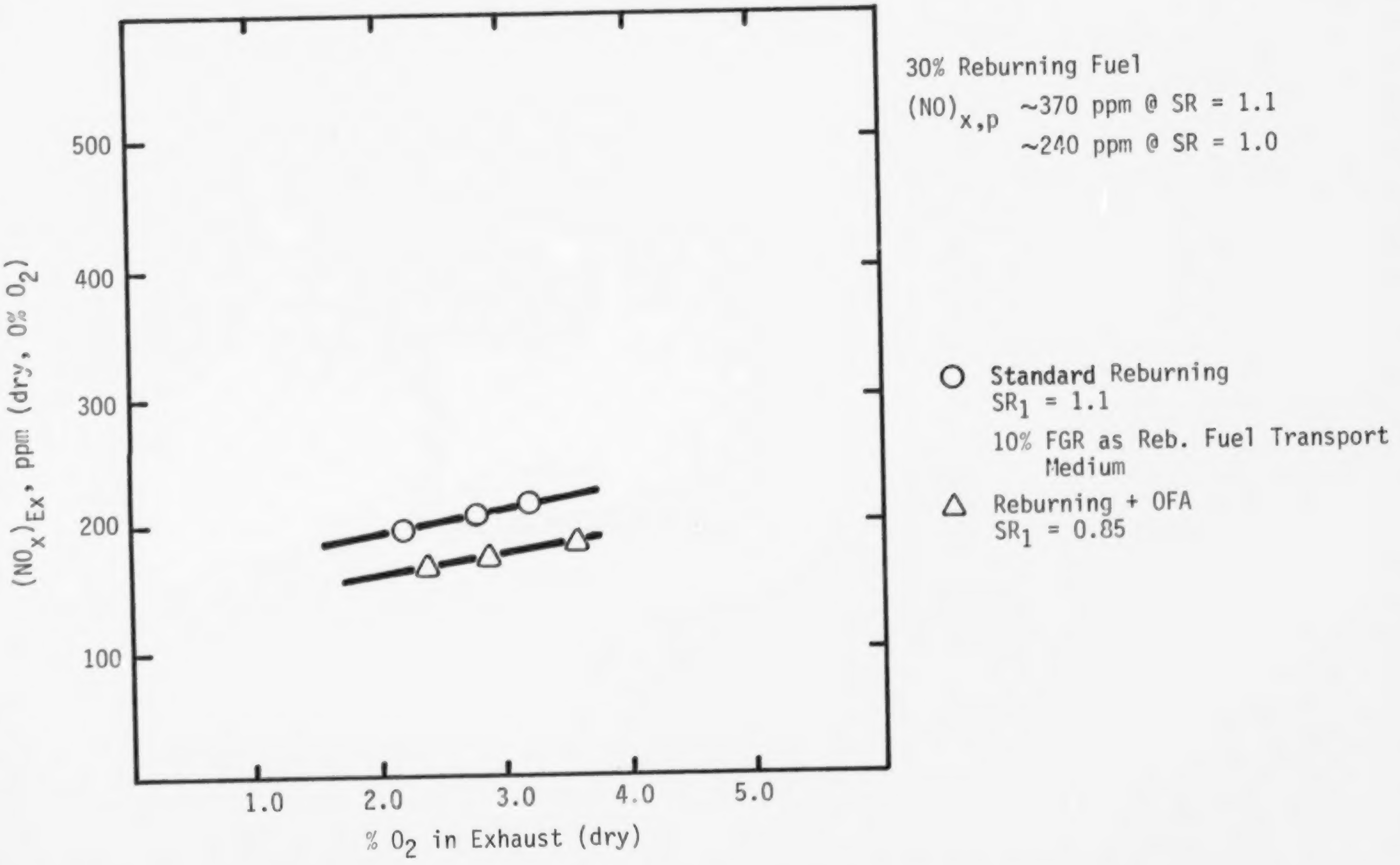


Figure 7-6. Comparison of NO_x emissions for standard and OFA plus reburning.

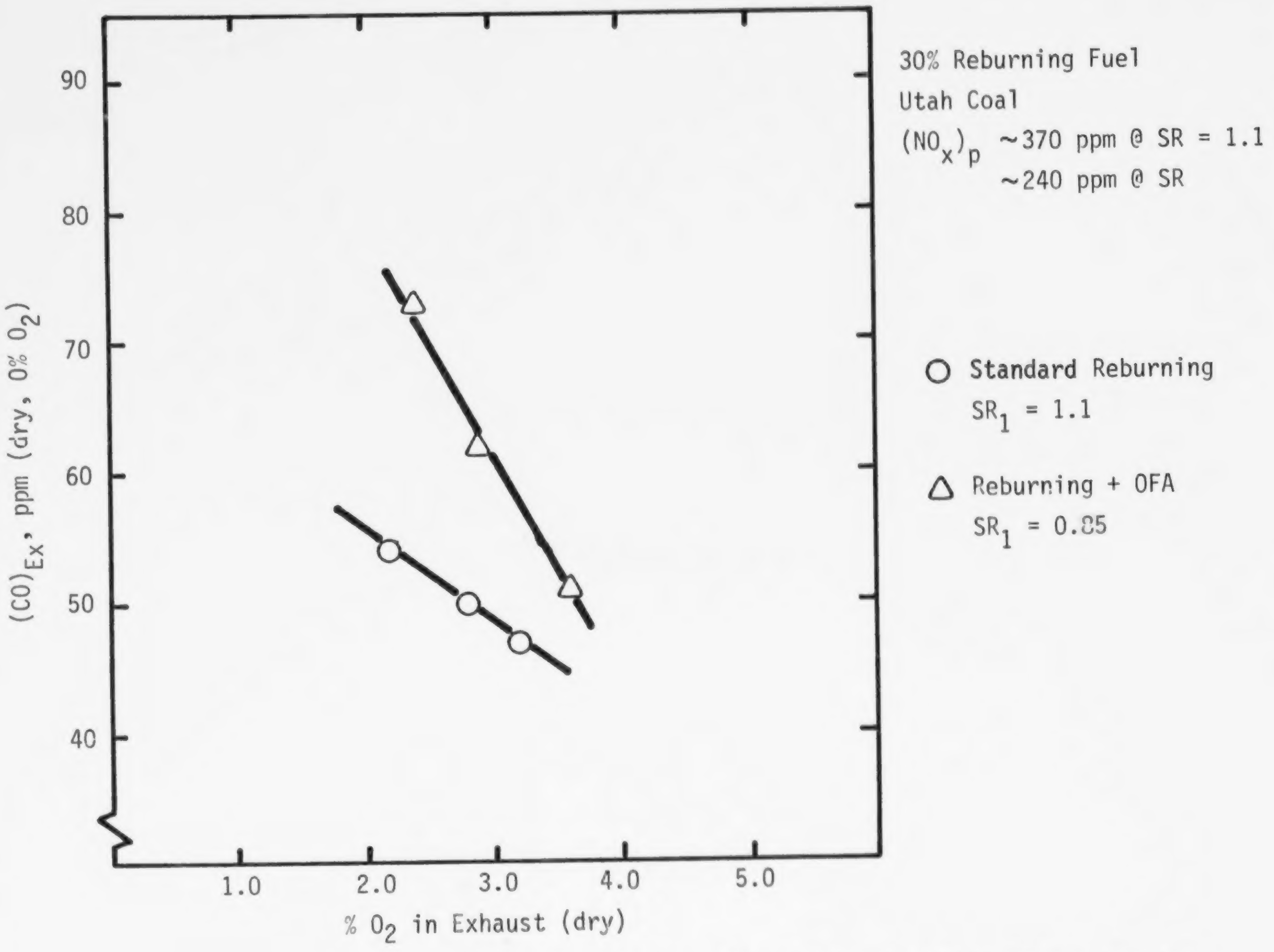


Figure 7-7. Comparison of CO emissions for standard and OFA plus reburning.

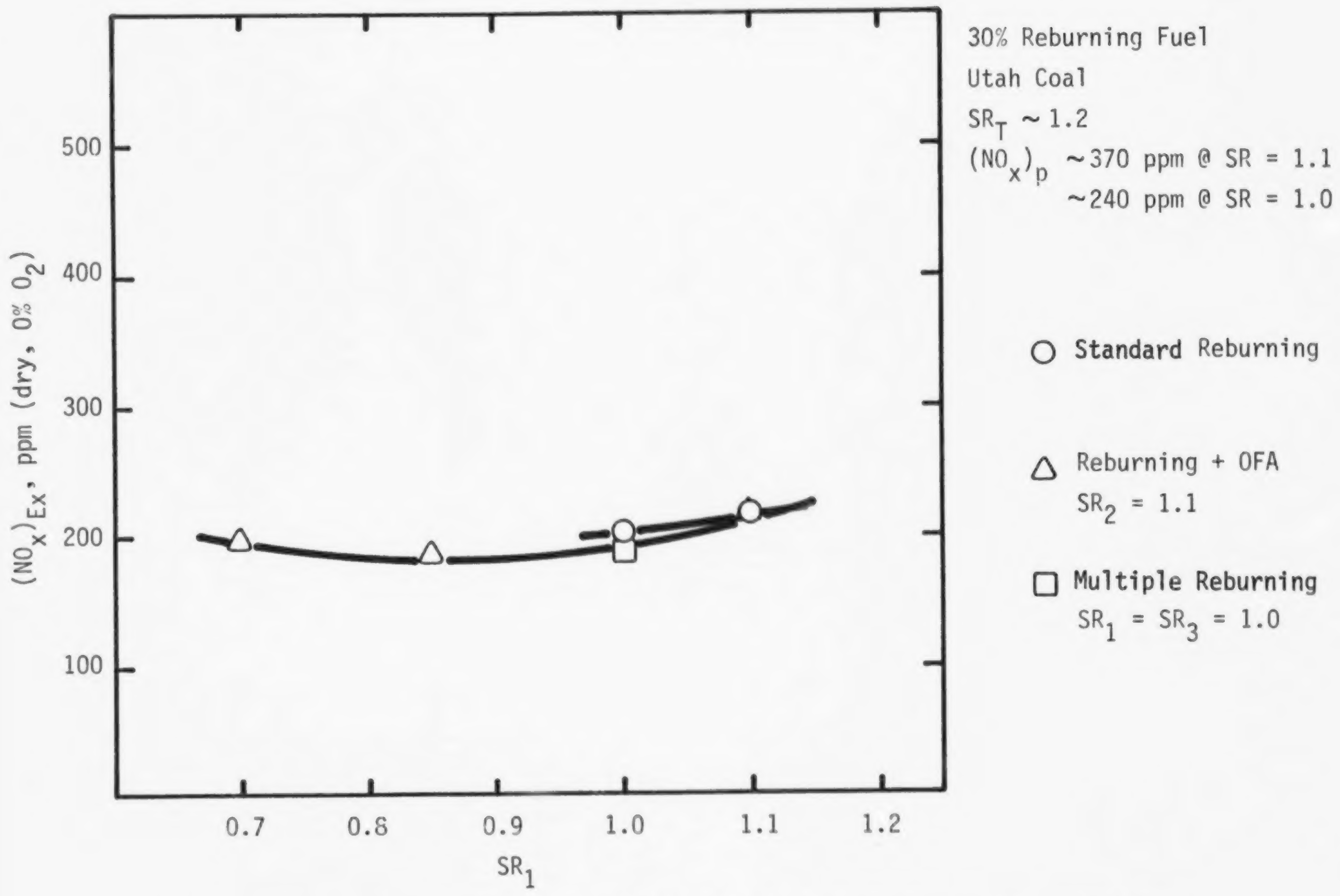


Figure 7-8. Effect of primary zone stoichiometry on NO_x emissions.

Baseline conditions for sorbent tests were as follows:

- 15 percent reburning fuel
- 4, 1 wall, 2.8" ID reburning jets
- 4 percent FGR
- $SR_1 = 1.0$, $SR_3 = 1.2$
- 8 opposed air jets:
  - 6,3.5" ID air jets
  - 2,1.7" ID sorbent jets
    1 on each wall, center ports, staggered
- Sorbent carrier air 60 scfm
- Uncontrolled SO_2 of 800-900 ppm (0% O_2)

S_x reduction was investigated using Genstar pressure laked lime and Colton lime plus 5 percent Na_2CO_3 additive as sorbents. Ca/S ratios from 0.3-2.3 were used. A comparison of the SO_2 capture for the Reburning Tower with that of the bench scale Boiler Simulator Furnace (BSF) is presented in Figure 7-9. Percent of SO_x captured on the pilot scale facility compared favorably with that found on the bench scale facility (Overmoe, et al., 1984). Genstar was found to be more effective than Colton + Na_2CO_3, with 41 percent capture observed at a Ca/S of 1.0. The figure indicates that high levels of capture are certainly achievable under reburning conditions. The fact that capture between the two facilities was almost identical may have been the result of a tradeoff between a more favorable temperature profile and a lesser degree of dispersion on the tower as compared to the BSF.

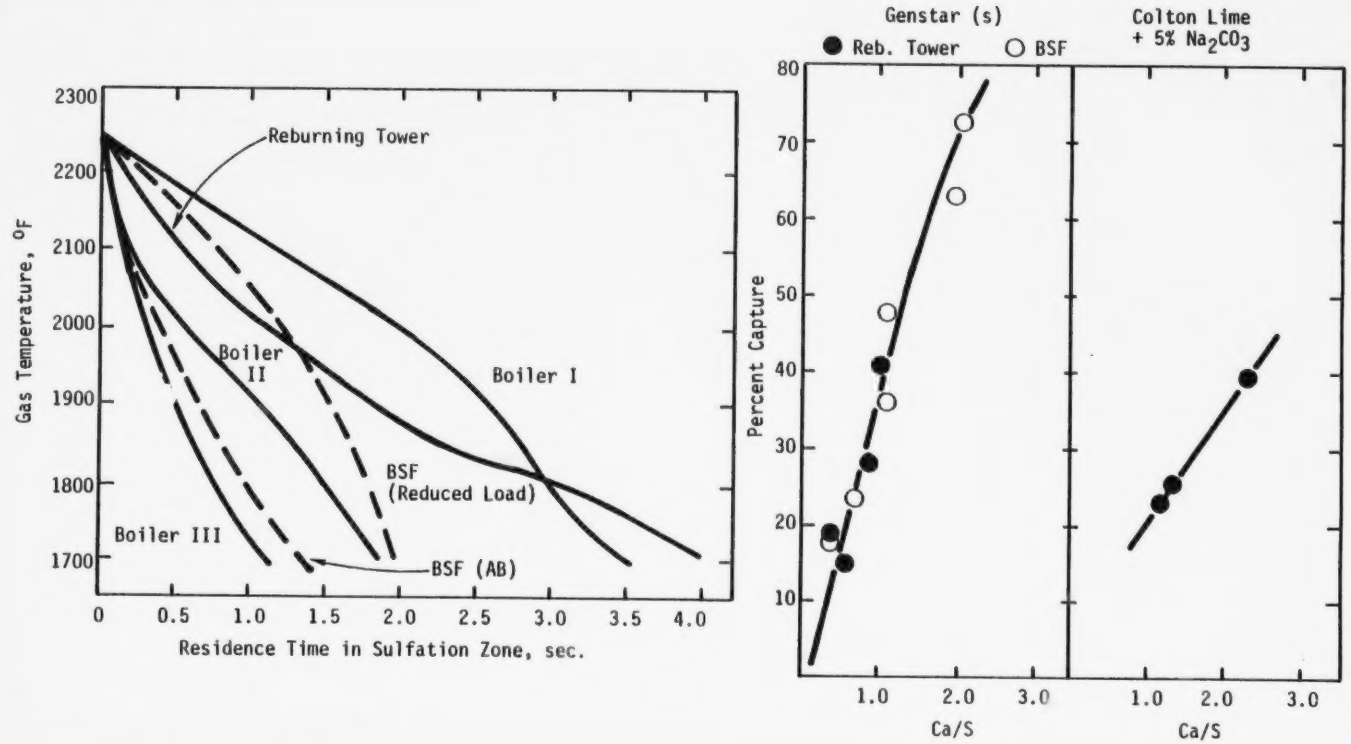


Figure 7-9. Comparison of SO_2 capture for Reburning Tower and Boiler Simulator Furnace (BSF).

8.0 DISCUSSIONS AND CONCLUSIONS

8.1 Scale Effect

The impact of scale on the reburning process was evaluated by direct comparison of results obtained on pilot and bench scale facilities. Test results from the bench scale CTT and pilot scale reburning tower are presented in Figure 8-1. The associated NO_x reduction is shown in Figure 8-2. Identical experimental procedures were followed on each facility, and the resultant data exhibited similar trends. Nearly ideal mixing probably occurred in the bench scale CTT (See Figure 5-1), whereas in the Reburning Tower, which was over 100 times larger in scale, the extent of mixing was likely not as good. The fact that emissions between the two facilities were similar may have been the result of a tradeoff between the reduction of $(NO_x)_p$, which was favored by fast mixing, and the minimization of fuel nitrogen conversion, which was favored by slow mixing between fuel and oxygen. These results suggest that as long as thorough reburning zone mixing is achieved, the NO_x reduction in a small scale facility can be approached in a facility of much larger size. It should be noted that the scale effect could be important in a full-scale boiler where the primary zone burnout might not be complete due to the use of coal or oil as the primary fuel.

8.2 Comparison with Other Studies

In studies completed in this program, it was shown that the effect of scale on NO_x emissions was small (see Section 8.1), and that parametric effects were similar in both bench and pilot scale facilities (See Chapter 4.0). A comparison of the results of several pilot scale studies is shown in Table 8-1. The NO_x reduction capabilities were similar for all of the systems. Since the reburning zone residence time was comparatively short for the EER baseline case, results obtained at a longer residence time are also shown. Reduction of uncontrolled emissions was in excess of fifty percent for all of the cases.

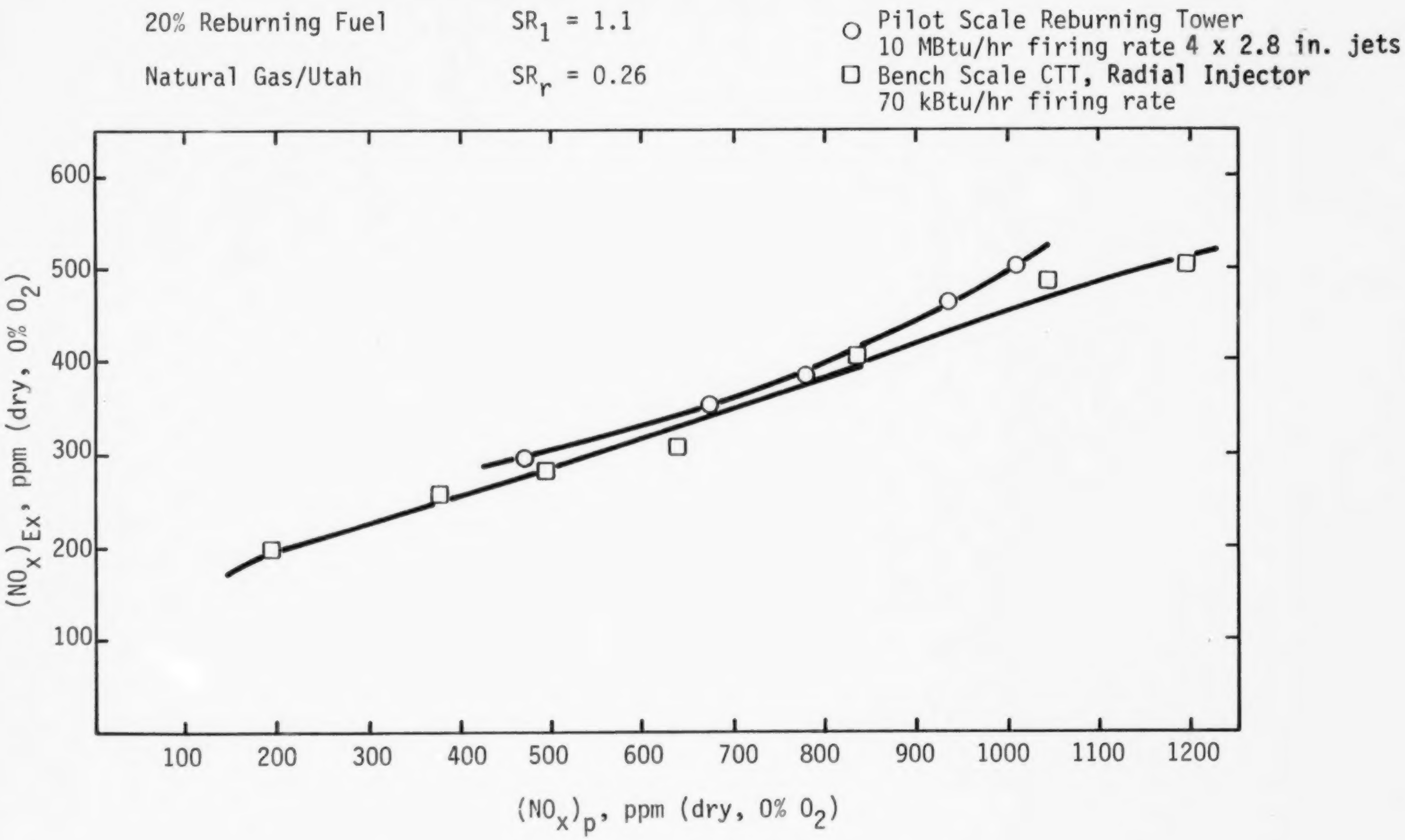


Figure 8-1. Influence of scale on the reburning process.

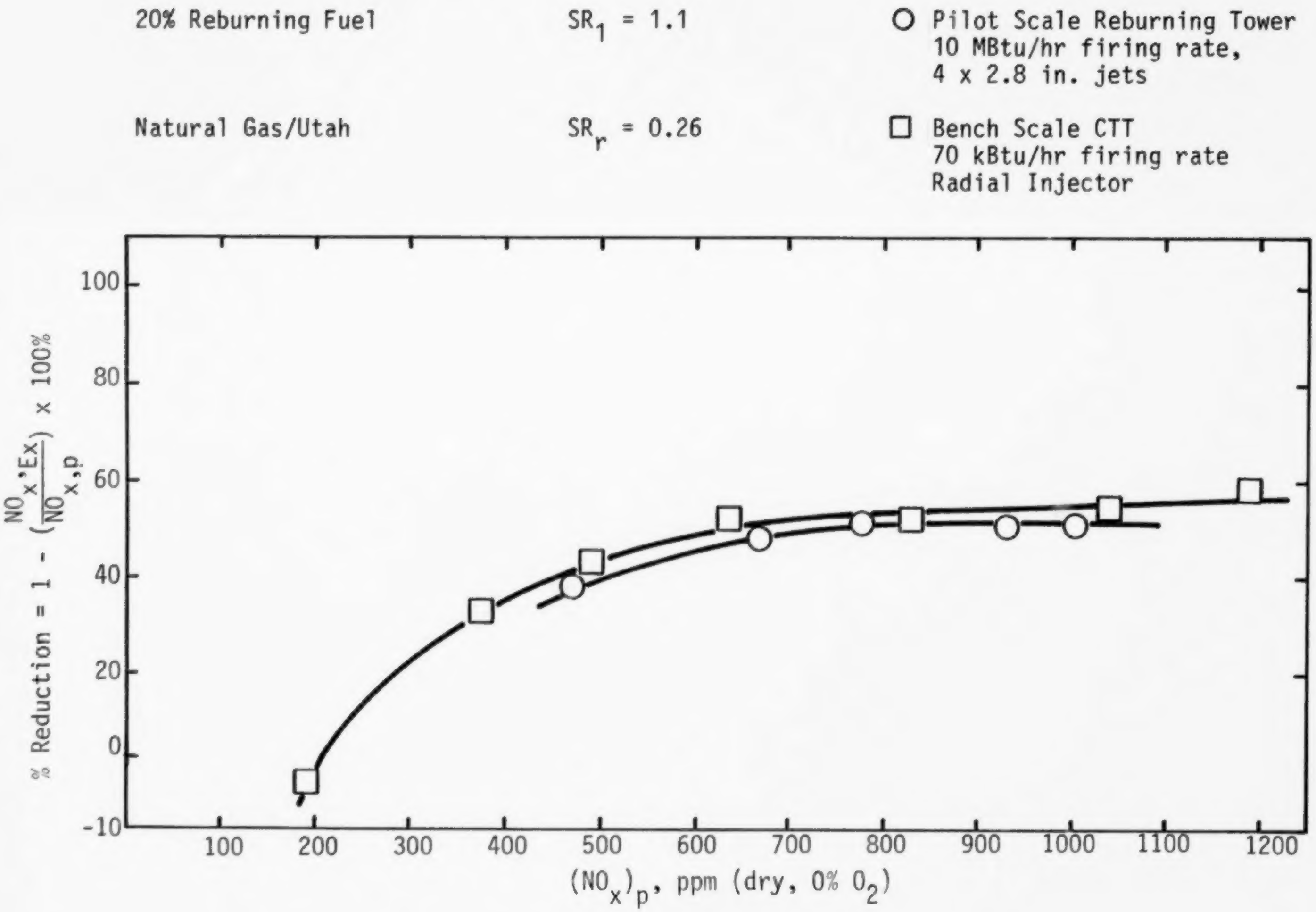


Figure 8-2. Scale effect on NO_x reduction capability.

TABLE 8-1. COMPARISON OF REBURNING STUDIES

Furnace	MHI(1) (tangential)	Riley Stoker(2)	Hitachi Zosen(3)	EER (short time) Profile 2	EER (long res. time) Profile 3
Total Load (MBtu/hr)	30	100	50	10	10
Uncontroled NO_x, ppm	280	500	700	600	575
SR_1	1.05	1.05	1.05	1.05	1.10
$(NO_x)_p$, ppm (dry, 0% O_2)	<140	<350	<550	~450	~345
% Reburning Fuel	10	20	30	15	20
SR_2	0.95	0.85	0.80	0.9	0.93
Transport Medium	FGR	Air	Air	FGR	FGR
Residence Time, (sec)	-	~2.0	~1.0	0.5	0.8
$(NO_x)_{Ex}$, ppm (dry, 0% O_2)	90	230	250	250	230
% Reduction	68	54	64	53	60
% Efficiency*	<36	<34	<55	44	33

(1) Takahashi, et al., 1981

(2) Lisauskas, 1984

(3) Sekiguchi, et al., 1984

* Molar Reduction of $(NO_x)_p$

The potential for greater NO_x reduction via multiple-staged reburning processes was not witnessed on the EER facility. A standard reburning process with a similar fuel-rich zone residence time appeared to be at least as efficient as the multi-staged processes, and since a standard process would involve less hardware, its implementation to a full scale boiler would be less costly.

8.3 Comparison with Staged Combustion

An overall comparison of the emissions levels achievable for uncontrolled combustion, staged combustion and reburning is made in Figure 8-3. For the staged and reburning data, the rich zone was run at 0.9 with the rich zone residence times as shown on the plot. With the application of staged combustion a substantial decrease in emissions over the uncontrolled emissions was achieved. The results when reburning was applied were even lower. Reburning produced emission levels that were about 100 ppm lower than the staged results even with much shorter rich zone residence times. Staged combustion could be made to generate lower emissions if even richer conditions were utilized. The major advantage of reburning technology over conventional staged combustion is that the burner region of the boiler can be operated in a fuel lean condition thereby avoiding potential slagging problems as opposed to a system where the entire front end is operated fuel rich.

8.4 Conclusions and Application Guidelines

The results of this study on the pilot scale Reburning Tower indicate that many chemical and physical parameters can affect the exhaust NO_x emissions produced under reburning conditions in a large scale combustion system. The fact that data generated on the Reburning Tower compare favorably with previous bench scale results suggests that the impact of major process parameters is independent of scale. Comparison of the data produced under identical conditions, except the extent of mixing, indicate that the effectiveness of reburning is also independent of scale. It was concluded

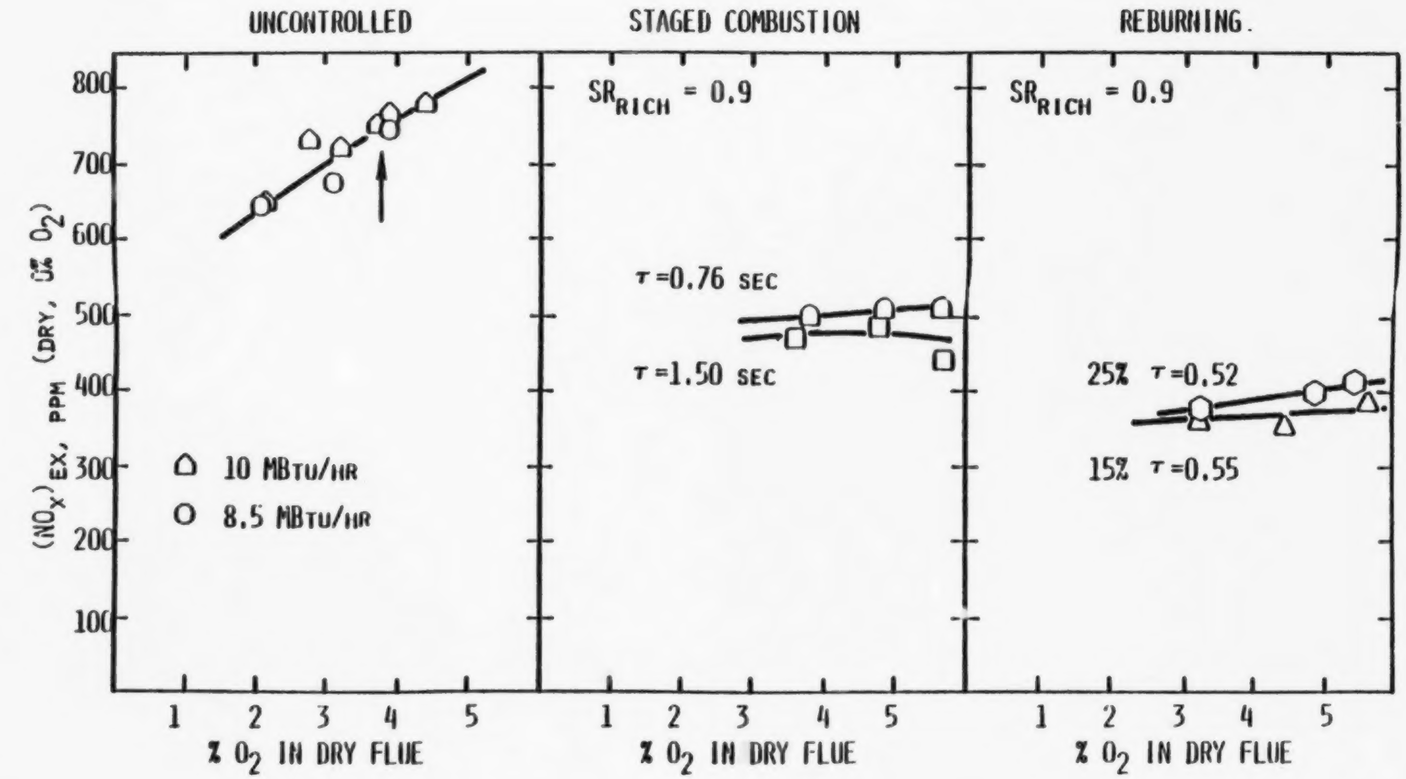


Figure 8-3. Reburning more effective than staged combustion under similar conditions

that in order to optimize the reburning process in terms of NO_x emissions the following guidelines should be observed:

- Minimize the level of excess air in the main burner zone.
- Minimize the available transport oxygen and in particular FGR should be used as a transport medium, if possible.
- The injection configuration with FGR should be arranged such that jet penetration is greater than half of the furnace depth, and cross-sectional coverage is thorough, with several jets spaced evenly on one wall.
- About 20 percent reburning fuel should be used.
- If air is used for reburning fuel transport, a higher amount of reburning fuel (up to 30 percent) and lower jet penetration should be used to obtain a fuel-rich reburning zone.
- Maximize the reburning zone residence time.
- Inject the reburning fuel in as hot a furnace environment as possible, but allow thorough primary zone burnout.

In addition, it was found that up to 60 percent reduction of primary NO_x can be attained, with lower primary NO_x levels hindering reduction efficiencies. Due to the lack of fuel nitrogen and transport medium oxygen, natural gas performs better as the reburning fuel than coal. The reburning process was found to be superior to staged combustion due to the smaller fuel-rich zone required for similar emissions and at least as efficient as multi-staged processes and is likely to be less costly to implement. Overall, the reburning process was shown to be an effective method for in-furnace NO_x reduction, substantially reducing NO_x emissions over values obtained under uncontrolled conditions.

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APPENDIX A

DATA ACQUISITION PROGRAM

A.0 REBURNING PROGRAM

The data acquisition system for the reburning tower requires that a special reburning program be written and implemented in the data acquisition system. The program calculated all of the air flowrates and stoichiometries for the three reburning zones, and corrected measured emissions to zero percent oxygen. Flexibility was built into the program for different fuels such as Utah coal in the primary and natural gas reburning. Table A-1 shows the program output format and a listing of the program follows:

TABLE A-1. DATA ACQUISITION PROGRAM OUTPUT

```
 DATE                 :     8-23-85
 SYSTEM               :     REBURNING
 PRI. FUEL            :     UTAH10
 REB. FUEL            :     UTAH10
                              PRIMARY                                                 SECONDARY
   TIME    FUEL(LB/HR)   VENT#  D.P.    TEMP   FLOW   SR1   FUEL(LB/HR)    VENT#  D.P.    TEMP   FLOW   SR2
   PT.#    C.L.(MBTU/HR)        (in WC) (F)    (SCFM)       C.L.(MBTU/HR)         (in WC) (F)    (SCFM)
           T.A.(SCFM)                                       T.A.(SCFM)
           C.P.(SCFM)                                       C.P.(SCFM)
 17:06:10      613.0     CA-1    8.50     99     79  1.09         0.0      CA-2    0.00   -316       0  1.69
   277           8.0     V -1   -0.88    489      0               0.0      FGR     1.72    184       0
              1337.3     V -3    5.04    549    572            1337.3
              1537.6     V -4   12.55    550    807            1537.6
                                       TOTAL   1458                                        TOTAL     0
 AUTO DATA


 REB.LEVEL            :     4
 REB.INJ.             :     4.1WL.2.8"
 BRNOUT LEV           :     7
 BRNOUT INJ           :     4.OPP.5.8"
                   TERTIARY                        EMISSIONS                  TEMPERATURES
 C.L.(MBTU/HR)  VENT#  D.P.    TEMP   FLOW   SR3       MEAS     0% O2              (F)
  T.L.(MBTU/HR)        (in WC)  (F)   (SCFM)
  C.P.(SCFM)
 Sam. P.(in WC)
      8.2       V -2   0.33    542      0  1.06   O2     1.2      0.0       OPEN   -373
      8.0                                         CO2   17.4     18.5       OPEN   -281
   1496.3                                         CO   105.3    111.8       OPEN     17
      0.00                                        NOx  345.8    347.1       OPEN     65
                       CUM TOTAL  1456            SO2 ------   ------       OPEN   -266
```

```
0: "KING KONG: REBURNING EXPERIMENT DATA ACQUISITION 1-10-85":
1: "MAIN":
2: sfg 14;deg
3: conv 36,45
4: dim A [9],B-[20],C-[75],D-[10,10],Y-[10,10],A[10,5],B[10],C[20],D[12]
5: dim H[2],K[5],F-[12,10],H-[20,10],K-[8,10],M-[12,10],S-[50],Z [10]
6: dim F[4],G[5,2],I[12],J[12],M[3],O[12],P[7],U[12]
7: dim D,R,X,Y,Z
8: for I=1 to 50;" "&S-→S-;next I
9: dsp "LOADING KEYS";trk 0;ldk 4
10: dsp "LOADING LABELS";ldf 5,475,11
11: cll 'F-L';cll 'A-L';cll 'V-L';cll 'S-L';cll 'T-C'
12: dsp "LOADING INFO";trk 0;ldf 6,475,13
13: cll '394';cll 'V-C';cll 'BURN'
14: dsp "LOADING M-P DATA";ldf 7,475,15
15: cll 'M-P'
16: 701→N;dev "N",N;wtb N,7
17: dsp "LOADING FUEL LIBRARY";ldf 8,475,18
18: cll 'F1'
19: cll 'SCALE';cll 'SPAN';1→A[1,1]→r12
20: "W":0→D;cll 'CLOCK';dsp "SCANNING"
21: if D=0;cll 'ANASCAN';cll 'VENTSCAN';cll 'TEMP';cll 'FLOW'
22: if D=0;if flg9 and flg4;cll 'PRINTER';cll 'RECORD'
23: if D=0;cll 'UPDATE';35+M[3]→M[3];cll 'TIME';dsp A-
24: if D<1 or D>24;jmp -3
25: jmp D
26: cll 'GOOD DATA';gto "W"
27: cll 'EDIT';gto "W"
28: cll 'VALID DATA';gto "W"
29: cll 'SPAN';gto "W"
30: cll 'SCALE';gto "W"
31: cll 'CALIBRATE';gto "W"
32: cll 'CORE';gto "W"
33: cll 'FUEL CHANGE';gto "W"
34: cll 'LOAD ASSIGNMENT';gto "W"
35: cll 'CARRIER AIR';gto "W"
36: cll 'COMMENT';gto "W"
37: stp ;gto "W"
38: cll 'ATO';gto "W"
39: cll 'PRINTER SWITCH';gto "W"
40: cll 'TAPE ON';gto "W"
41: cll 'TAPE SWITCH';gto "W"
42: 1→r12;0→D;gto 21
43: cll 'FGRVENT';gto "W"
44: 0→D;gto 21
45: 10→Z;cll 'SPOINT';gto 37
46: 9→Z;cll 'SPOINT';gto 37
47: 8→Z;cll 'SPOINT';gto 37
48: 7→Z;cll 'SPOINT';gto 37
49: 6→Z;cll 'SPOINT';gto 37
50: stp
51: end
52: "*********  INPUTS  *********":
53: "CORE":
54: cfg 2;cfg 3
```

```
55: ent "IS THERE BURNOUT AIR?",Z-;if Z-="n";sfg 2
56: ent "IS THERE REBURNING AIR?",Z-;if Z-="n";sfg 3;jmp 3
57: ent "IS REB AIR FLUE GAS?",Z-;cfg 7;if Z-="n";jmp 2
58: ent "ENTER %O2 IN FLUE:",P;sfg 7
59: " "→Z-;ent "TEMPERATURES?",Z-;if Z-="y";cll 'ENTER'
60: ""→Z-;ent "PRESSURE READINGS ?",Z
61: if Z-#"y";jmp 3
62: enp "SAMPLE P=?",H[1]
63: " "→Z-;ent "Change Load?",Z-;if Z-#"y";jmp 2
64: cll 'LOAD ASSIGNMENT'
65: ret
66: "ENTER":
67: " "→Z-;ent "Venturi Temps?",Z-;if cap(Z-)="N";jmp 2
68: for I=1 to 7;dsp H-[I],"=?";enp "",C[I];next I
69: " "→Z-;ent "Furnace Temps?",Z-;if cap(Z-)="N";jmp 2
70: for I=8 to 18;dsp H-[I],"=?";enp "",C[I];next I
71: ret
72: "CARRIER AIR":ent "Enter Delta P. for PRI AIR(inH2O):",B[1]
73: ent "Enter STATIC P for PRI AIR(PSIG):",B[8]
74: ent "Enter Delta P. for REB AIR(in.H2O):",B[2]
75: ent "Enter STATIC P for REB AIR(PSIG):",B[9];ret
76: "CLOCK":dsp "ENTER TIME";wait 999;ent "HOURS?",M[1];ent "MINUTES?",M[2]
77: ent "SECONDS",M[3];cll 'TIME';ret
78: "TIME":fxd 0;if M[3]>=60;1+M[2]→M[2];(M[3]/60-1)*60→M[3]
79: if M[2]>=60;1+M[1]→M[1];(M[2]/60-1)*60→M[2]
80: str(M[1])→A-[1];if val(A-[1])<9.5;"0"&A-[2]→A-[2]
81: str(M[2])→A-[4];if val(A-[4])<9.5;"0"&A-[5]→A-[5]
82: str(M[3])→A-[7];if val(A-[7])<9.5;"0"&A-[8]→A-[8]
83: A-[2,3]&":"&A-[5,6]&":"&A-[8,9]→A-
84: ret
85: "COMMENT":
86: ""→Z-;ent "CHANGE LABEL ?",Z-
87: if Z-#"y";jmp 4
88: for I=1 to 8;dsp Y-[I]&" ?"
89: ent "",D-[I];cap(D-[I])→D-[I]
90: next I
91: dsp "ENTER COMMENT";beep
92: ent "",C-;cap(C-)→C-
93: ret
94: "OK":cfg 5;""→Z-;ent "OK?",Z-;if cap(Z-[1,1])="Y";sfg 5
95: ret
96: "FGRVENT":
97: ent "Is FGR measured with large venturi? ",Z-
98: if Z-="y";2984→P[5];ret
99: 736.4→P[5];ret
100: "*******  M-P  ROUTINES  ***********":
101: "UPDATE":cfg 1;sfg 4
102: fmt 5,c7,x,f4.0,x;fmt 6,c8,x,f5.0,x
103: fmt 7,c11,x,f5.0,x;fmt 8,c4,x,5f5.1;if D=0;cll 'TRANSFER'
104: if D=0;wrt .5,"PRI AIR",A[6,1];wait 2000
105: if D=0;wrt .6,"REB AIR",A[6,2];wait 2000
106: if D=0;wrt .7,"BURNOUT AIR",A[6,3];wait 2000
107: if D=0;wrt .8,"CONC",K[1],K[2],K[3],K[4],K[5];wait 2000
108: ret
```

```
109: "TRANSFER":for J=1 to 12;0→I[J];next J
110: for J=1 to 12;for I=0 to 11
111: if D≠0;ret
112: cll 'SE'(402,1,I);rI→U[I+1];I[I+1]+U[I+1]/O[I+1]→I[I+1];next I;next J
113: for J=1 to 12;I[J]/12→I[J];next J;0→Z
114: if D=0;cll 'KT'(9.1,C[1],9.2,C[2],9.3,C[3],9.4,C[4],9.5,C[5],9.6,C[6])
115: if D≠0;ret
116: cll 'KT'(10.1,C[7],10.2,C[8],10.3,C[9],10.4,C[10],10.5,C[11],10.6,C[12])
117: 1→Z;if D≠0;jmp 2
118: cll 'KT'(8.1,C[13],8.2,C[14],8.3,C[15],8.4,C[16],8.5,C[17],8.6,C[18])
119: ret
120: "Parameter Check":
121: "PC":if flg8≠1;mdec;dev "MP",9;wti 0,9;sfg 8
122: fmt 9,c,f2.0,/,c,f2.0,2/
123: if int(p0/2)=p0/2;1+p0→p0;0→pp0
124: fxd 0;moct;1→p39
125: if pp39>=400 and pp39<=414;pp39-400→pp39
126: if pp39>=0 and pp39<=14;jmp 2
127: dsp "Slot Address p",p39,"out of range";stp ;jmp -2
128: if p(p39+1)<=7777;jmp 2
129: dsp "Data, p",p39+1,"out of range";stp ;jmp -1
130: if (p39+2→p39)<=p0-1;gto -5
131: if pp0<=15;jmp 2
132: dsp "Unit no.",pp0,"out of range";stp ;jmp -1
133: ret
134: "Single Ended Scan":
135: "SE":cll 'Parameter Check'(p1,0,p4);12*(p1+1)→p5
136: if p2<1 or p2>168-p5;prt "Total readings,",p2,"out of range";stp ;jmp 0
137: if p3<0 or p3>168-p5;prt "Starting channel,",p3,"out of range";stp ;jmp 0
138: if p2+p3>168-p5;prt "Last channel,",p2+p3,">168";stp ;jmp -2
139: wtb "MP",170140+dtop4
140: prnd(.49+(p2+p3)/12,0)→p6
141: 1→p39
142: wtb "MP",10000*dto(p1+p39)
143: if (p39+1→p39)<=p6;gto -1
144: wtb "MP",170160+dtop4
145: p3→p39
146: prnd(.51+p39/12,0)→p5
147: wtb "MP",10000*dto(p1+p5)+dto(2^(p39mod12))
148: wtb "MP",170260+dtop4
149: wti 4,10000*dtop1;rdb("MP")→rp39
150: wtb "MP",170160+dtop4,10000*dto(p1+p5)
151: if rp39>7777;rp39-100000→rp39
152: otdrp39→rp39;if rp39>2047;rp39-4096→rp39
153: .05rp39→rp39
154: if (p39+1→p39)<p2+p3;gto -8
155: wtb "MP",170040;mdec
156: ret
157: "SCALE":fxd 0;prt "ANALYZER SCALE";spc
158: for I=1 to 5;prt M-[I],J[I];next I;spc 2;cll 'OK';if flg5;jmp 3
159: for I=1 to 5;dsp M-[I]&"-METER FULLSCALE?";ent "",J[I];next I
160: jmp -3
161: ret
```

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162: "ANASCAN":for J=1 to 5;I[J]*J[J]→K[J];next J;ret
163: "SPAN":fxd 0;prt "Venturi Scale";spc
164: for I=11 to 7 by -1;prt M-[I],J[I];next I;spc 2;cll 'OK';if flg5;jmp 3
165: for I=11 to 7 by -1;dsp M-[I]&"IN. FULLSCALE?";ent "",J[I];next I
166: jmp -3
167: ret
168: "VENTSCAN":for J=11 to 7 by -1;I[J]*J[J]→B[14-J];next J
169: B[3]→B[10];B[4]→B[3];B[10]→B[4];B[5]→B[10];B[7]→B[5];B[6]→B[7];B[10]→B[6]
170: ret
171: "K Thermocouple":
172: "KT":gsb "Parameter Check"
173: 3923.7225→p60;13.158→p61;273.2→p62
174: 39.448872→p51;2.4548362e-2→p52;-9.0918433e-6→p53
175: 2.5132785e-2→p41;-6.0883423e-8→p42
176: 5.5358209e-13→p43;9.3720918e-18→p44
177: 1→p39
178: wtb "MP",170160+dtopp0
179: if (10frc(pp39)→p38)<7;gto +2
180: beep;prt "Address p",p39,"out of range";stp ;gto -1
181: wtb "MP",10000dtoint(pp39)+7,170260+dtopp0
182: wti 4,10000dtoint(pp39);rdi 4→p37
183: (otdp37-4096)*10/4352→p37
184: p60/(p61+ln(-p37))-p62→p37
185: p37(p51+p37(p52+p37p53))1e-6→p37
186: wtb "MP",170160+dtopp0,10000dtoint(pp39)+p38,170260+dtopp0
187: wti 4,10000dtoint(pp39);rdi 4→p36
188: if Z=1;((otdp36→p36)-(p36>2047)4096)5e-5→p36;jmp 2
189: ((otdp36→p36)-(p36>2047)4096)1e-5→p36
190: (p37+p36)1e6→p36
191: p40+p36(p41+p36(p42+p36(p43+p36p44)))→p(p39+1)
192: if (p39+2→p39)<=p0-1;gto -14
193: wtb "MP",170040;mdec
194: ret
195: "TEMP":for I=1 to 18;1.8*C[I]+32→C[I];next I;ret
196: "SPOINT":if Z=0;ret
197: cll 'SE'(402,1,Z);rZ/O[Z+1]*J[Z+1]→X
198: fxd 2;dsp M-[Z+1],X;fxd 0;jmp -2
199: ret
200: "CALIBRATE":for J=1 to 12;0→I[J];next J
201: for J=1 to 12;for I=6 to 11
202: cll 'SE'(402,1,I);rI→U[I+1];I[I+1]+U[I+1]/O[I+1]*J[J+1]→I[I+1];next I
203: next J
204: for I=7 to 11;I[I]/12→I[I];next I;fxd 2
205: if I[11]<=.1;prt "VENT-CALIBRATION"
206: if I[11]<=.1;prt "----------------"
207: if I[11]<=.1;prt D-[1]&"  "&A-[1,5];spc 2
208: if I[11]<=.1;prt "      ZERO"
209: if I[11]>.1;prt "     SPAN"
210: for I=11 to 7 by -1;prt M-[I],I[I];next I;spc 2;fxd 0
211: ret
212: "*********  COMPUTATIONS  *********":
213: "FLOW":
214: for I=3 to 7;if B[I]<.01;0→D[I];jmp 2
215: P[I]*\(B[I]/(C[I]+460))→D[I]
216: next I
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217: if flg2;0→D[3]
218: if flg3;0→D[5]
219: for I=1 to 2;if B[I]<.01;0→D[I];jmp 2
220: 276*\(B[I]/(C[I]+460))*\((B[I+7]+14.7)/14.7)→D[I]
221: next I
222: if flg7;D[5]*P/21→A[6,2];D[5]-A[6,2]→A[7,2];jmp 2
223: D[5]→A[6,2];0→A[7,2]
224: A[6,2]+D[2]→A[6,2]
225: cll 'COMPUTE';ret
226: "COMPUTE":for I=1 to 5;K[I]→G[I,1];next I
227: A[2,1]*r20/1e6→A[3,1]
228: A[2,1]*r23/60→A[4,1]
229: D[1]+D[4]→A[6,1]
230: A[6,1]+D[6]+D[7]→A[9,1]
231: A[9,1]/A[4,1]→F[1]
232: r19/(100-r19)→r50
233: .155(F[1]-1)A[4,1]/A[2,1]→r71
234: A[2,1]*6.45(r22+r71+r50/18+r14/200)→A[5,1]
235: A[5,1]+A[6,2]+A[7,2]→A[5,2]
236: A[2,2]*r37/1e6→A[3,2]
237: A[4,1]+A[2,2]*r40/60→A[4,2]
238: (A[9,1]+A[6,2])/A[4,2]→F[2]
239: A[3,1]+A[3,2]→A[4,3]
240: A[2,1]+A[2,2]→A[2,3]
241: D[3]→A[6,3]
242: A[9,1]+A[6,2]+A[6,3]→A[10,1]
243: r36/(100-r36)→r51
244: 1+G[1,1]r58/(100-4.76G[1,1])r59→F[3]
245: 4.76F[3]*r57+(r54/28+r56/32-r53/4)/100+.155A[7,2]→A[2,4]
246: 6.45((A[2,1]r50+A[2,2]r51)/18+.005(A[2,1]r14+A[2,2]r31)+A[2,4])→A[5,3]
247: A[10,1]/F[3]→A[4,4]
248: 60*A[4,4]*(r20A[2,1]+r37A[2,2])/r60(A[2,1]+A[2,2])→A[3,4]
249: 21/(21-G[1,1])→Z;0→G[1,2];for I=2 to 5;Z*G[I,1]→G[I,2];next I
250: ret
251: "**********  PRINTER ROUTINES  **********":
252: "ATO":
253: if flg9;cfg 9;prt "AUTO START OFF";spc 2;ret
254: if flg9=0;sfg 9;prt "AUTO START ON";spc 2
255: ret
256: "PRINTER SWITCH":
257: if flg11;cfg 11;beep;prt "PRINTER OFF";spc 2;ret
258: if flg11#1;sfg 11;prt "PRINTER ON";spc 2
259: ret
260: "PRINTER":if flg11=0;ret
261: time 0
262: if int((r12-1)/7)*7=r12-1;cll 'INFO';cll 'HFADING'
263: cll 'FORMAT'
264: wtb N,27,38,107,50,83
265: for I=1 to 5;if I=1;wrt "N.1",A-
266: if I=2;fmt 1,4x,f4.0,4x,z;wrt "N.1",A[1,1]
267: fmt 1,c,z
268: if I=5;jmp 16
269: for J=1 to 3
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270: if I=4;if J=3;wrt "N.5",H[1];wrt "N.1",S-[1,41];jmp 13
271: if I=1;if J=3;wrt "N.2",A[3,4]/1e6
272: if I>1;if J=3;wrt "N.2",A[I+2,J]
273: if I>2;if J=1;wrt "N.1",S-[1,12]
274: if J<3;wrt "N.2",A[I+1,J]
275: if I=2;if J=3;wrt "N.1",S-[1,37];jmp 8
276: if I=3;if J=2;wrt "N.1",S-[1,37];jmp 7
277: if I=3;if J=3;wrt "N.1",S-[1,37];jmp 6
278: if I=4;if J=2;wrt "N.1",S-[1,37];jmp 5
279: if I=1;wrt "N.3",F-[J],B[J],C[J],D[J],F[J]
280: if I=2;wrt "N.4",F-[J+3],B[J+3],C[J+3],D[J+3]
281: if I=3;wrt "N.4",F-[J+5],B[J+5],C[J+5],D[J+5]
282: if I=4;wrt "N.4",F-[J+6],B[J+6],C[J+6],D[J+6]
283: next J
284: if I=5;wrt "N.8",S-[1,44],"TOTAL  ",A[9,1],S-[1,40],"TOTAL  "
285: if I=5;wrt "N.9",A[6,2],S-[1,36],"CUM TOTAL  ",A[10,1],S-[1,8]
286: wrt "N.6",F-[I+7],G[I,1],G[I,2]
287: wrt "N.7",H-[I+7],C[I+7]
288: wtb N,13,10;next I
289: fmt 1,c,z;fmt 2,f4.1,z;fmt 3,f3.0,z
290: wrt "N.1","AUTO DATA ";if flg10#1;jmp 5
291: if D#1;jmp 3
292: wrt "N.1","VALID DATA POINT #",B-
293: wrt "N.1","  ELAPSED TIME, MIN ";wrt "N.2",H[2]
294: wrt "N.1","  RECORD ON TRK";wrt "N.3",X;wrt "N.1","FILE";wrt "N.3",Y
295: wrt "N.1",C-;if flg10=0;""→C-
296: wtb N,13,10,10
297: r12+1→r12;A[1,1]+1→A[1,1];cfg 4
298: ret
299: "HEADING":
300: wtb N,27,38,107,50,83;wtb N,13,27,38,100,68
301: fmt 2,227x;wrt "N.2";wtb N,13,27,38,100,65
302: fmt 1,c,z;wtb N,13
303: wrt "N.1",S-[1,38],"PRIMARY",S-[1,44],"SECONDARY",S-[1,42]
304: wrt "N.1","TERTIARY",S-[1,26],"EMISSIONS",S-[1,20],"TEMPERATURES"
305: wtb N,13,10
306: wrt "N.1","    TIME       FUEL(LB/HR)   VENT#   D.P.     TEMP   FLOW"
307: wrt "N.1","   SR1    FUEL(LB/HR)   VENT#   D.P.     TEMP   FLOW   SR2"
308: wrt "N.1","   C.L.(MBTU/HR)  VENT#   D.P.    TEMP   FLOW   SR3"
309: wrt "N.1","         MEAS      0% O2",S-[1,22],"(F)"
310: wtb N,13,10
311: wrt "N.1","    PT.#     C.L.(MBTU/HR)         (in WC)   (F)   (SCFM)"
312: wrt "N.1","        C.L.(MBTU/HR)         (in WC)   (F)   (SCFM)      "
313: wrt "N.1","    T.L.(MBTU/HR)        (in WC)   (F)   (SCFM)"
314: wtb N,13,10
315: wrt "N.1",S-[1,14],"T.A.(SCFM)",S-[1,41],"T.A.(SCFM)",S-[1,41]
316: wrt "N.1","C.P.(SCFM)"
317: wtb N,13,10
318: wrt "N.1",S-[1,14],"C.P.(SCFM)",S-[1,41],"C.P.(SCFM)"
319: wrt "N.1",S-[1,40],"Sam. P.(in WC)"
320: wtb N,13,27,38,100,68;wrt "N.2";wtb N,13,27,38,100,65
321: ret
```

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322: "INFO":
323: wtb N,27,38,107,49,83
324: fmt 1,c10," :",2x,c10,z
325: fmt 3,c,z
326: wtb N,13,12,10
327: for I=1 to 4;wtb N,13,10
328: len(Y-[I])→r1;len(D-[I])→r2
329: len(Y-[I+4])→r3;len(D-[I+4])→r4
330: wrt "N.1",Y-[I]&S-[1,10-r1],D-[I]&S-[1,10-r2]
331: wrt "N.3",S-[1,10]
332: wrt "N.1",Y-[I+4]&S-[1,10-r3],D-[I+4]&S-[1,10-r4]
333: next I
334: ret
335: "FORMAT":
336: fmt 0
337: fmt 1,2x,c8,2x,z
338: fmt 2,4x,f6.1,4x,z
339: fmt 3,2x,c4,3x,f5.2,4x,f4.0,3x,f4.0,2x,f4.2,2x,z
340: fmt 4,2x,c4,3x,f5.2,4x,f4.0,3x,f4.0,8x,z
341: fmt 5,6x,f4.2,z
342: fmt 6,3x,c3,x,f6.1,4x,f6.1,4x,z
343: fmt 7,4x,c5,4x,f4.0,z
344: fmt 8,c,c,f4.0,c,c,z
345: fmt 9,f4.0,c,c,f4.0,c,z
346: ret
347: "*****  TAPE DRIVE ROUTINES  *****":
348: "TAPE ON":
349: on err "TAPE ERR"
350: dsp "INSERT UNPROTECTED DATA TAPE";beep;stp
351: if bit(7,rds(1))=1;dsp "Slide TAPE TAB to RECORD";stp ;jmp 0
352: trk 0;fdf 0;idf r1,r2,r3,r4,r5
353: if r2#2 or r3#8;dsp "NOT DATA TAPE";wait 999;jmp -3
354: 0→r1;ent "Tape ID ?",r1
355: ldf 0,Z
356: if Z=r1;jmp 3
357: ""→Z-;if flg1;dsp "TAPE ID is",Z,"Want to change ?";ent "",Z-
358: if cap(Z-[1,1])="Y";cll 'ASSIGN';jmp -3
359: dsp "TAPE ID is confirmed -",Z;wait 999
360: cll 'SEARCH'
361: if Y=0;dsp "TAPE FULL";wait 999;jmp -11
362: jmp 4
363: "TAPE ERR":on err "TAPE ERR"
364: if bit(2,rds(1))=1;jmp -14
365: if rom=0 and ern=41;jmp -15
366: on err "ERR"
367: ret
368: "ASSIGN":
369: ent "TAPE ID Assignment ?",Z
370: dsp "User Defined ID",Z,"OK ?"
371: ent "",Z-;if cap(Z-[1,1])#"Y";jmp -2
372: trk 0;rcf 0,Z
373: ret
374: "SEARCH":
375: on err "SEARCH ERR"
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376: 0→X→Y
377: trk 1
378: 10→r8;1→r7
379: for I=r8 to r7 by -1
380: fdf I
381: idf r1,r2,r3,r4,r5
382: dsp "TRACK",r5,"FILE",r1
383: if r2#0 and r2#3;prt "NON DATA FILE",r1
384: if r1=1 and r3=0 and r5=1;dsp "TRACK 1 EMPTY";trk 0;jmp -6
385: if r4=0 and r5=1;beep;jmp 13
386: if r5=0 and r4=0;dsp "TRACK 0 FULL";beep;1→X;1→Y;jmp 12
387: if r1=r8 and r3#0;r8+10→r8;r7+10→r7;jmp -8
388: if r3#0;jmp 2
389: next I
390: r5→X;I+1→Y
391: prt "RECORD start at TRACK",X,"FILE",Y
392: sfg 1
393: jmp 5
394: "SEARCH ERR":
395: on err "SEARCH ERR"
396: if rom=0 and ern=65;jmp -7
397: dsp char(rom),ern,erl;stp
398: on err "ERR"
399: ret
400: "ERR":
401: on err "ERR"
402: if rom=0 and ern=15;dsp "OUT OF PAPER";beep;stp
403: dsp "ERROR ",ern," at ",erl;stp
404: ret
405: "TAPE SWITCH":
406: if flg10;cfg 10;prt "TAPE OFF";spc 2;ret
407: if flg10#1;sfg 10;prt "TAPE ON";spc 2
408: ret
409: "RECORD":
410: if flg10=0;ret
411: if X=0 and Y=0;cll 'TAPE ON'
412: if bit(7,rds(1))=1;dsp "TAPE PROTECTED";jmp 0
413: trk X;fdf Y
414: idf r1,r2,r3,r4,r5
415: if r4=0 and r5=0;dsp "TRACK 0 FULL, START TRACK 1";1→X;1→Y;jmp -2
416: if r4=0 and r5=1;beep;dsp "TAPE FULL";wait 999;cll 'TAPE ON';jmp -3
417: if r3>8;dsp "FILE",Y,"is NOT EMPTY";beep;wait 999;Y+1→Y;jmp -4
418: dsp "Recording on TRK",X,"FILE",Y
419: trk X;rcf Y,A-,B-,C-,D-,Y-,A[*],B[*],C[*],D[*],H[*],K[*]
420: fxd 0
421: if flg11#1;prt "RECORD ON","TRACK"&str(X)&" FILE"&str(Y);spc 2
422: Y+1→Y;""→C-;ret
423: "*****  VALID DATA RECORDING *****":
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424: "GOOD DATA":
425: ent "REPRESENTATIVE CONDITION AT TRK?",r1;if flg13;jmp 0
426: ent "REPRESENTATIVE CONDITION AT FLE?",r2;if flg13;jmp 0
427: trk r1;ldf r2,A-,B-,C-,D-,Y-,A[*],B[*],C[*],D[*],H[*],K[*]
428: prt A-;spc 2;cll 'OK';if flg5#1;jmp -3
429: for I=1 to 5;dsp M-[I]&"?";ent "",K[I];next I
430: 0→B→Q;enp "ELAPSED TIME ,min ?",H[2];if flg13;jmp 0
431: cll 'OK';if flg5#1;jmp -1
432: enp "VALID DATA PT# ?",B-;cll 'OK';if flg5#1;jmp 0
433: cll 'CORE';cll 'COMMENT';cll 'COMPUTE'
434: cll 'PRINTER';cll 'RECORD'
435: ret
436: "VALID DATA":1→D
437: ent "Valid Data Pt at Trk?",r1;if flg13;jmp 0
438: ent "Valid Data Pt at File?",r2;if flg13;jmp 0
439: r1→X;r2→Y
440: trk r1;ldf r2,A-,B-,C-,D-,Y-,A[*],B[*],C[*],D[*],H[*],K[*]
441: prt A-;cll 'OK';if flg5#1;jmp -4
442: cll 'COMPUTE';cll 'PRINTER'
443: ""→Z-;ent "MORE VALID DATA POINTS ?",Z-
444: if cap(Z-)="Y";jmp -7
445: ret
446: "EDIT":
447: ent "Valid data pt at TRK ?",r1
448: ent "Valid data pt at File ?",r2
449: trk r1;ldf r2,A-,B-,C-,D-,Y-,A[*],B[*],C[*],D[*],H[*],K[*]
450: r1→X;r2→Y
451: prt A-;cll 'OK';if flg5#1;jmp -4
452: " "→Z-;ent "ANY CHANGES ?",Z-
453: if cap(Z-)="N";jmp 16
454: " "→Z-;ent "AIR , TEMP CHANGES ?",Z-
455: if cap(Z-)="N";jmp 5
456: for I=1 to 5
457: dsp "VENTURI ",I,"FLOW ?";ent "",D[I+1]
458: dsp "VENTURI ",I,"TEMP ?";ent "",C[I+1]
459: next I
460: ""→Z-;ent "CONCENTRATION CHANGES ?",Z-
461: if cap(Z-)="N";jmp 2
462: for I=1 to 5;dsp M-[I]&" ?";ent "",K[I];next I
463: ""→Z-;ent "BURNER & FURNACE SETTING CHANGES ?",Z-
464: if cap(Z-)="N";jmp 2
465: cll 'CORE'
466: ent "VALID DATA PT # ?",B-
467: ent "ELAPSED TIME, min ?",H[2]
468: cll 'COMMENT'
469: ent "RECORD ON TRK",X;ent "FILE",Y
470: cll 'COMPUTE';cll 'RECORD'
471: ""→Z-;ent "More data to edit ?",Z-
472: if cap(Z-)="Y";jmp -25
473: ret
474: end
475: "F1":2→Z
476: dim W-[Z,10]
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477: "UTAH10"→W-[1];"N.GAS"→W-[2];ret
478: "F2":2→Z;for J=1 to Z;prt W-[J];next J;spc 2;ret
479: "FUEL":cfg 1;for I=3 to 4;for J=1 to Z
480: if D-[I]=W-[J];if I=3;cll '2';next I
481: if D-[I]=W-[J];if I=4;gto "2"
482: next J;sfg 1;ret
483: "2":if J=1;if I=3;72.42→r13;5.58→r14;1.36→r15;.55→r16;11.02→r17;9.15→r18
484: if J=1;if I=3;4.26→r19;12958→r20;ret
485: if J=2;if I=3;72.77→r13;23.04→r14;1.94→r15;0→r16;.59→r17;0→r18→r19
486: if J=2;if I=3;21088→r20;ret
487: if J=1;if I=4;72.42→r30;5.58→r31;1.36→r32;.55→r33;11.02→r34;9.15→r35
488: if J=1;if I=4;4.26→r36;12958→r37;ret
489: if J=2;if I=4;72.77→r30;23.04→r31;1.94→r32;0→r33;.59→r34;0→r35→r36
490: if J=2;if I=4;21088→r37;ret
491: "COMP":
492: (r13/12+r14/4+r16/32-r17/32)/100→r21
493: 1842r21→r23
494: (r13/12+r15/28+r16/32+376.19r21)/100→r22
495: r13/12(79r21/21+r21)→r24
496: (r13/12+r15/28+r16/32-100r21)/100(79r21/21+r21)→r25
497: (r30/12+r31/4+r33/32-r34/32)/100→r38
498: 1842r38→r40
499: (r30/12+r32/28+r33/32+376.19r38)/100→r39
500: r30/12(79r38/21+r38)→r41
501: (r30/12+r32/28+r33/32-100r38)/100(79r38/21+r38)→r42
502: for J=13 to 17
503: A[2,1]*rJ+A[2,2]*r(J+17)→r(J+39);next J
504: .01(r52/12+r53/4+r55/32-r56/32)→r57
505: r57/(A[2,1]+A[2,2])→r59
506: 1842r59→r60
507: (r52/12+r54/28+r55/32+376.19r57)/100(A[2,1]+A[2,2])→r58
508: ret
509: "FUEL CHANGE":
510: prt "CURRENT PRI FUEL    "&D-[3]
511: prt "BTU/LB",r20;spc 2
512: prt "CURRENT REB FUEL    "&D-[4]
513: prt "BTU/LB",r37;spc 2
514: cll 'F2'
515: ent "PRI FUEL?",D-[3];cap(D-[3])→D-[3]
516: ent "REB FUEL?",D-[4];cap(D-[4])→D-[4]
517: cll 'FUEL'
518: if flg1;prt "fuel not in library";spc 2;jmp -2
519: fxd 2
520: for I=3 to 4
521: if I=3;prt "PRI FUEL - ",D-[I]
522: if I=4;prt "REB FUEL - ",D-[I]
523: for J=1 to 6
524: if I=3;prt K-[J]&"%",r(J+12);next J;prt "BTU/HR",r20;spc 2
525: if I=4;prt K-[J]&"%",r(J+29);next J;prt "BTU/LB",r37;spc 2
526: if I=3;1→Q;jmp 2
527: 2→Q
```

```
528: cll 'LOAD ASSIGNMENT'
529: next I
530: ret
531: "LOAD ASSIGNMENT":
532: ent "Which Fuel(Prim.=1,Reb.=2)?",Q
533: if A[8,Q]#0;prt "MEASURED LOAD",A[8,Q]/1e6
534: if Q=1;if D-[3]="UTAH10";jmp 6
535: if Q=2;if D-[4]="UTAH10";jmp 5
536: ent "NAT. GAS ROTAMETER SETTING?",r75
537: ent "NAT. GAS PRESSURE(psig)?",r76
538: .0747*.65r75\((r76+14.7)/19.7)→A[2,Q]
539: jmp 2
540: ent "FUEL (lbs/hr) ?",A[2,Q]
541: A[2,Q]*r23/60→R;A[2,Q]*r20→A[8,Q]
542: prt "CHANGED LOAD",A[8,Q]/1e6,"T.A",R;spc 2
543: cll 'COMP'
544: ret
545: end
*29735
```

APPENDIX B

QUALITY ASSURANCE

B.0 QUALITY ASSURANCE

The collection of and analysis of quality data has been the primary objective of this program. In order to ensure that the reported data is accurate, many quality assurance steps have been taken in all phases of the program. The Quality Assurance Plan submitted for the entire reburning program defines tolerance levels for all of the measurements that were taken. This appendix describes the measurements, systems, and special checks that were made during the program to monitor data quality.

B.1 Measurement Methods

B.1.1 Gas Species

Exhaust and in-flame gas species were measured with the use of the SWS sampling system. Concentrations of NO_x, O_2, CO_2, and CO were taken from the exhaust section of the reburning tower with a water-cooled probe located at the center of the duct. The sample train for the continuous gas species is shown in Figure B-1. The sample gas was passed through water condensers and a filter and was pumped into the control room for analysis. Every morning before testing, a leak check on the sample system was performed by plugging the probe and checking the ball on the sample rotameter. If the ball did not drop to zero, then a leak in the system was present and required repair.

Figure B-2 shows a schematic of the analytical system used for this program. The SO_2 monitoring system shown was not used for this program. For reburning zone mapping tests, the THC analyzer was tapped into the sample line. The system was identical to that used for previous SWS programs except for the data acquisition program which was rewritten for reburning calculations. A listing of the program is given in Appendix A. Table B-1 lists all of the instruments used for the continuous gas monitoring and the range of each. Instrument calibrations were performed about every 2-3 hours

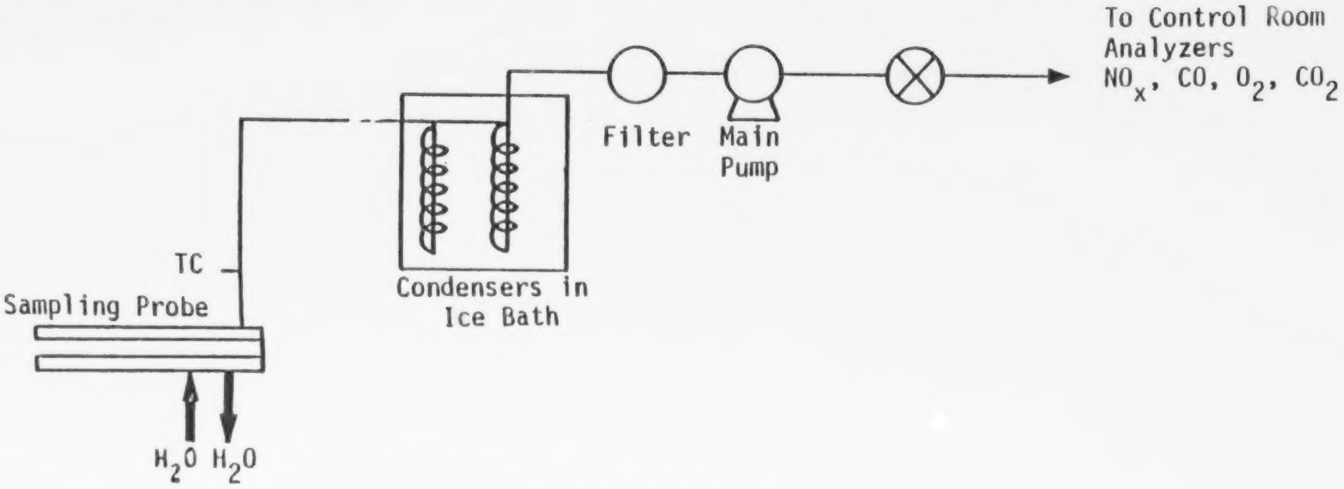
To Control Room
Analyzers
NO_x, CO, O_2, CO_2
Filter
Main Pump
Condensers in Ice Bath
TC
Sampling Probe
H_2O
H_2O

Figure B-1. Continuous gas species sample train.

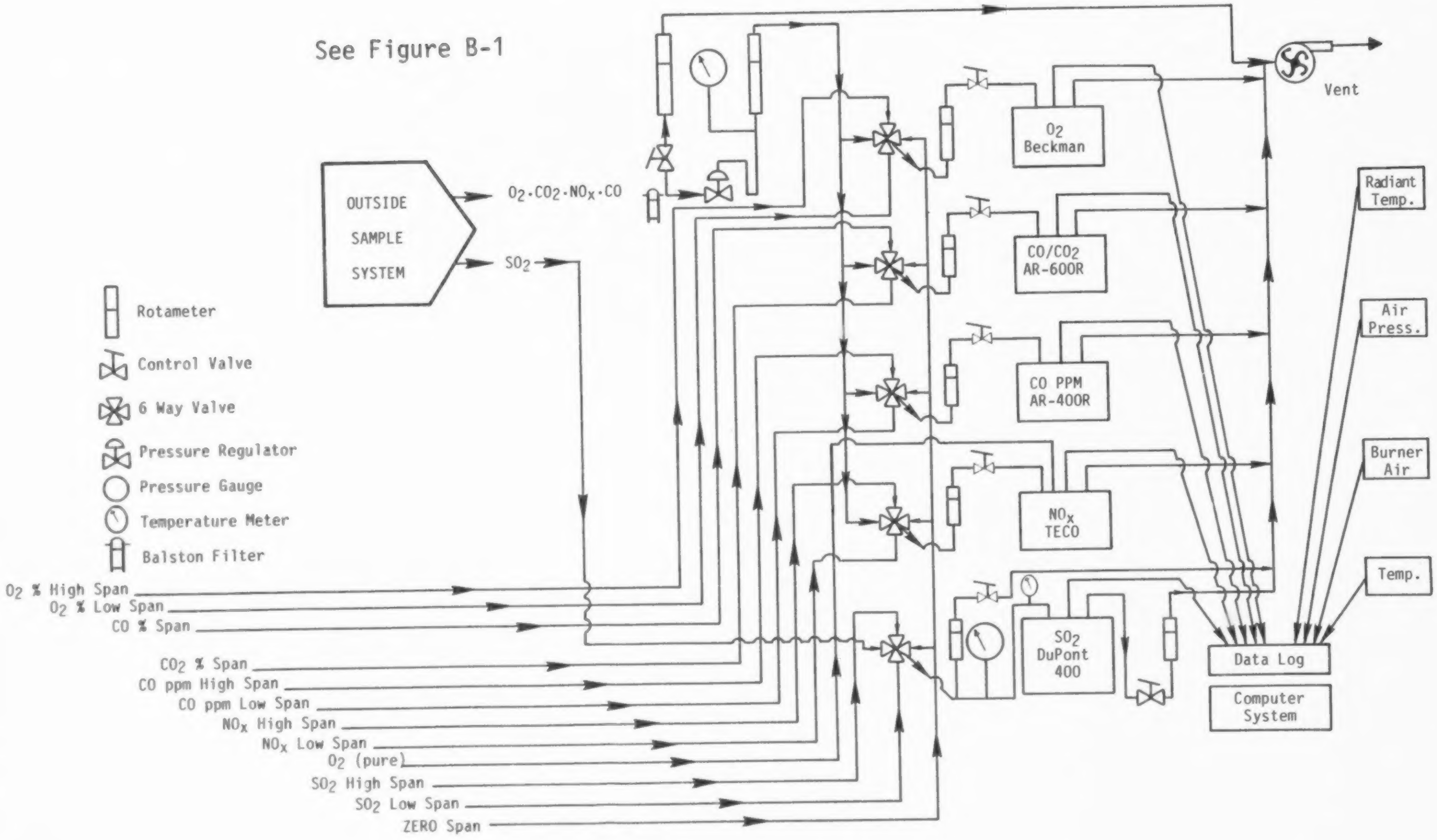
See Figure B-1
OUTSIDE
SAMPLE
SYSTEM
$O_2 \cdot CO_2 \cdot NO_x \cdot CO$
SO_2
Rotameter
Control Valve
6 Way Valve
Pressure Regulator
Pressure Gauge
Temperature Meter
Balston Filter
O_2 % High Span
O_2 % Low Span
CO % Span
CO_2 % Span
CO ppm High Span
CO ppm Low Span
NO_x High Span
NO_x Low Span
O_2 (pure)
SO_2 High Span
SO_2 Low Span
ZERO Span
O_2 Beckman
CO/CO_2 AR-600R
CO PPM AR-400R
NO_x TECO
SO_2 DuPont 400
Vent
Radiant Temp.
Air Press.
Burner Air
Temp.
Data Log
Computer System

Figure B-2. Reburning tower analytical system.

TABLE B-1. CONTINUOUS GAS ANALYSIS INSTRUMENTS

Gas Measured	Detection Principle	Manufacturer	Model No.	Range
NO, NO_2	Chemiluminescent	Thermo Electron Corp. (TECO)	10 AR	0-1000 ppm
CO	Nondispersive Infrared (NDIR)	Anarad, Inc.	AR500R	0-500 ppm
CO_2	Nondispersive Infrared (NDIR)	Anarad, Inc.	AR500R	0-20%
O_2	Paramagnetic	Beckman Instruments, Inc.	755	0-10%
C_xH_y	Flame Ionization (Heated)	Beckman Instruments, Inc.	402	0-5000 ppm

during testing in addition to the calibrations performed at the beginning and end of each day. Calibration gases were certified standard grade mixtures, compared by the manufacturer to primary standard gas mixtures (NBS traceable, gravimetrically prepared). Table B-2 lists the span gases used and their respective concentrations. A series of Quality Assurance Checks were conducted on all of the instruments several months before this program began. Instrument performance tests were conducted to determine the relative accuracy, calibration error and 2-3 hour drift. Table B-3 summarizes these results. The relative accuracy was determined by comparing the instrument values to values obtained using EPA Reference Methods from a previous program. There is currently no performance specification for the CO monitor or standard reference method for CO determination, but calibration error and 2-hour drift tests were conducted in accordance with the guidelines for the other analyzers. The results showed that the O_2 and CO_2 span were above the EPA spec. All others fell within the specific tolerance.

Table B-4 indicates the actual versus program goals for precision, accuracy, and completeness for the gas species measurements.

B.2 Burner and Downstream Air Flowrates

The air flowrates to the main burner and various points downstream were measured with Calibrated Venturi flowmeters. All of the combustion air was preheated by a heat exchanger that intercepted the hot exhaust gases from the tower. For this program, the preheat air temperatures were several hundred degrees lower than for previous SWS programs because the transport lines were extended by an additional 50 feet to bring air to the top of the tower. Also the exhaust gases had much more space to cool off before entering the heat exchanger immediately downstream of the SWS.

The flowmeters are routinely calibrated before each test series by pitot tube measurements and calculations. The pitot tube calibrations yielded a constant for each Venturi from which air flow measurements were then made. The air flowrates were determined from the measured pressure drop in each venturi and the air temperature according to:

TABLE B-2. CALIBRATION GASES

Gas	Concentration	Percent of Full Scale	Balance Gas	Grade
NO	787 ppm	79	Nitrogen	Certified Standard
O_2	9.0%	90	Nitrogen	Certified Standard
CO_2	15.0%	75	Nitrogen	Certified Standard
CO	250 ppm	50	Nitrogen	Certified Standard
CH_4	500 ppm	10	Nitrogen	Certified Standard

TABLE B-3. INSTRUMENT PERFORMANCE TESTS SUMMARY

Instrument/ Manufacturer	Relative Accuracy		Calibration Error			2-3 Hour Drift Test			
	%	EPA Spec	Mid	High	EPA Spec	Zero	EPA Spec	Cali- bration	EPA Spec
O_2--Beckman	19.2	≤20	1.48	-1.03	≤5.0	0.19	≤0.4	0.55	≤0.4
CO_2--Anarad, Inc.	2.9	≤20	0.56	4.23	≤5.0	0.22	≤0.4	2.12	≤0.4
NO/NO_x--TECO	9.88	≤20	0.74	-0.20	≤5.0	0.04	≤2.0	1.58	≤2.0
CO--Anarad, Inc.	-	-	6.06	-1.25	-	1.05	-	3.66	-

Note: O_2 & CO_2 -- EPA Method 3 (Orsat)

NO_x -- EPA Method 7

TABLE B-4. PROGRAM OBJECTIVES FOR GAS SPECIES MEASUREMENT PRECISION, ACCURACY, AND COMPLETENESS

Gas	Measurement Method	Precision: % Rel. Standard Deviation		Accuracy, %		Completeness, %	
		Actual	Goal	Actual	Goal	Actual	Goal
NO/NOx	Chemiluminescense	259	2	9.9	20	90	90
CO	NDIR	148	2	-	20	90	90
CO_2	NDIR	2.00	2	2.9	20	90	90
O_2	Paramagnetic	0.49	2	19.2	20	90	90
Gas Temperature	Suction Pyrometer with S-type thermocouple	.31	5	2.5	5	90	90

$$\dot{m} = K\rho_0 \sqrt{\Delta P/T}$$

where m is the mass flow of air, P is the venturi pressure drop in inches of H_2O, T is the absolute temperature in °R and K is the dimensional venturi constant. The K constants calculated from the calibrations performed before this program are given in Table B-5 along with four previous calibrations. The average relative standard deviation for the three venturis used was 3.9 percent.

B.3 Temperatures

The furnace exit temperature and the gas temperatures in the furnace were measured with single shield suction pyrometers. Figure B-3 shows the tip construction of the suction pyrometer. K and S-type thermocouples were used in these pyrometers depending on the temperature levels. These thermocouples were manufactured according to the ASTM standards. The error limits for K-type thermocouple are ± 2.2°C or ± 0.75 percent of the reading (whichever is greater). The error limits for S-type thermocouple are ± 1.5°C or ± 2.5 percent of the measured temperature (whichever is greater). These pyrometers were calibrated to determine the optimum suction gas flowrate for temperature measurements. The calibration curve is shown in Figure B-4. During temperature measurements the suction flowrates were monitored by an orifice meter in the suction stream. In all tests, the suction flow rate was such that the pressure drop across the orifice flowmeter was kept above 0.20 inches of H_2O.

B.4 Solids Composition

Solid samples were taken from the furnace at the exhaust and also in-flame. The sampling system used for solids was described in Chapter 2.0. Coal and ash samples were analyzed in EER's laboratory for carbon, hydrogen, nitrogen, ash, and moisture using a Perkin-Elmer 240B elemental analyzer. Table B-6 shows the precision, accuracy and completeness data for this

TABLE B-5. REBURNING TOWER VENTURI FLOWMETER CALIBRATIONS

Calibration Date	Venturi Calibration Constant, K*		
	Venturi #2	Venturi #3	Venturi #4
10/31/84	8778	8707	7111
01/07/84	8448	7764	7216
10/01/84	8448	8437	7132
12/20/84	8011	7399	6772
7/2/85	7963	8097	7243
Average	8330	8081	7095
Standard Dev.	305.0	465.7	68.8
Rel. St. Dev., %	3.66	5.76	2.38

*$M = K\rho_0\sqrt{\Delta P/T}$

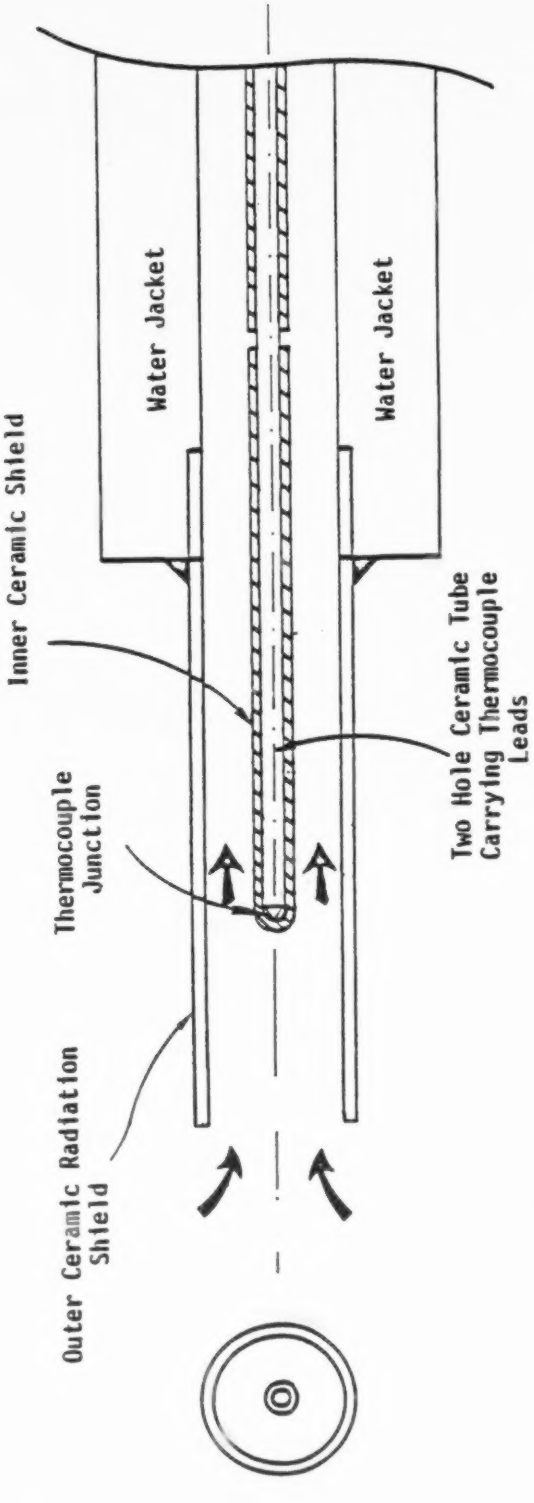
Outer Ceramic Radiation Shield
Thermocouple Junction
Inner Ceramic Shield
Two Hole Ceramic Tube Carrying Thermocouple Leads
Water Jacket
Water Jacket

Figure B-3. Suction pyrometer tip construction.

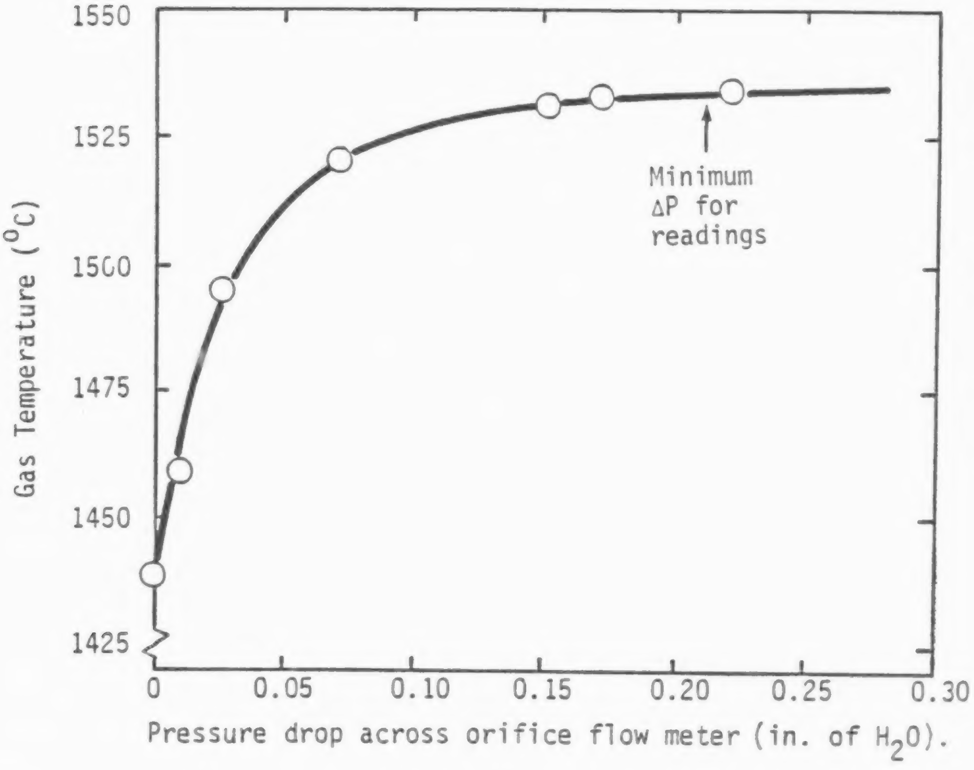

Figure B-4. Suction flowrate calibration for suction pyrometer.

TABLE B-6. SOLIDS PRECISION, ACCURACY, AND COMPLETENESS.

Gas Measured	Precision (%)		Accuracy (%)		Completeness (%)	
	Actual	Goal	Actual	Goal	Actual	Goal
Fuel Composition						
Carbon	.24	2	0.8	2	95	90
Hydrogen	1.38	5	0.6	5	95	90
Nitrogen	2.13	10	1.9	10	95	90
Ash	0.33	10	1.42	10	95	90
Moisture	2.55	10	8.71	10	95	90

instrument. These results were generated during a prior EPA audit. The numbers obtained from the solids analyses were used to calculate primarily percent burnout of the coal.

B.5 Other Checks and Measurements

B.5.1 System Mass Balance Check

As an independent check on the fuel flowrate, the fuel composition, the composition of combustion products in the exhaust and the measured air flowrates were used to calculate the thermal heat input into the furnace. This was routinely compared with the calculated heat input based on fuel heating value and mass flowrate for natural gas. This procedure was performed every test day before the testing commenced. This procedure allowed the engineer to check the proper operation of the Reburning Tower systems and to identify any problems. The checks this procedure provided include:

- Gas sampling system leak check
- Combustion air measurement system check
- Fuel flow rate measurement check
- Furnace leak check

The results of these checks performed during the test period are shown in Figure B-5. Tests were not conducted unless the calculated and measured loads were within 10 percent.

B.5.2 System Uncontrolled NO_x Check

In order to ensure consistency in data obtained throughout the program, uncontrolled NO_x levels were checked each day before reburning was applied. The primary firing to be used on that day was attained and measured emissions were compared to those of the baseline curve. A sampling of the data at 8.0

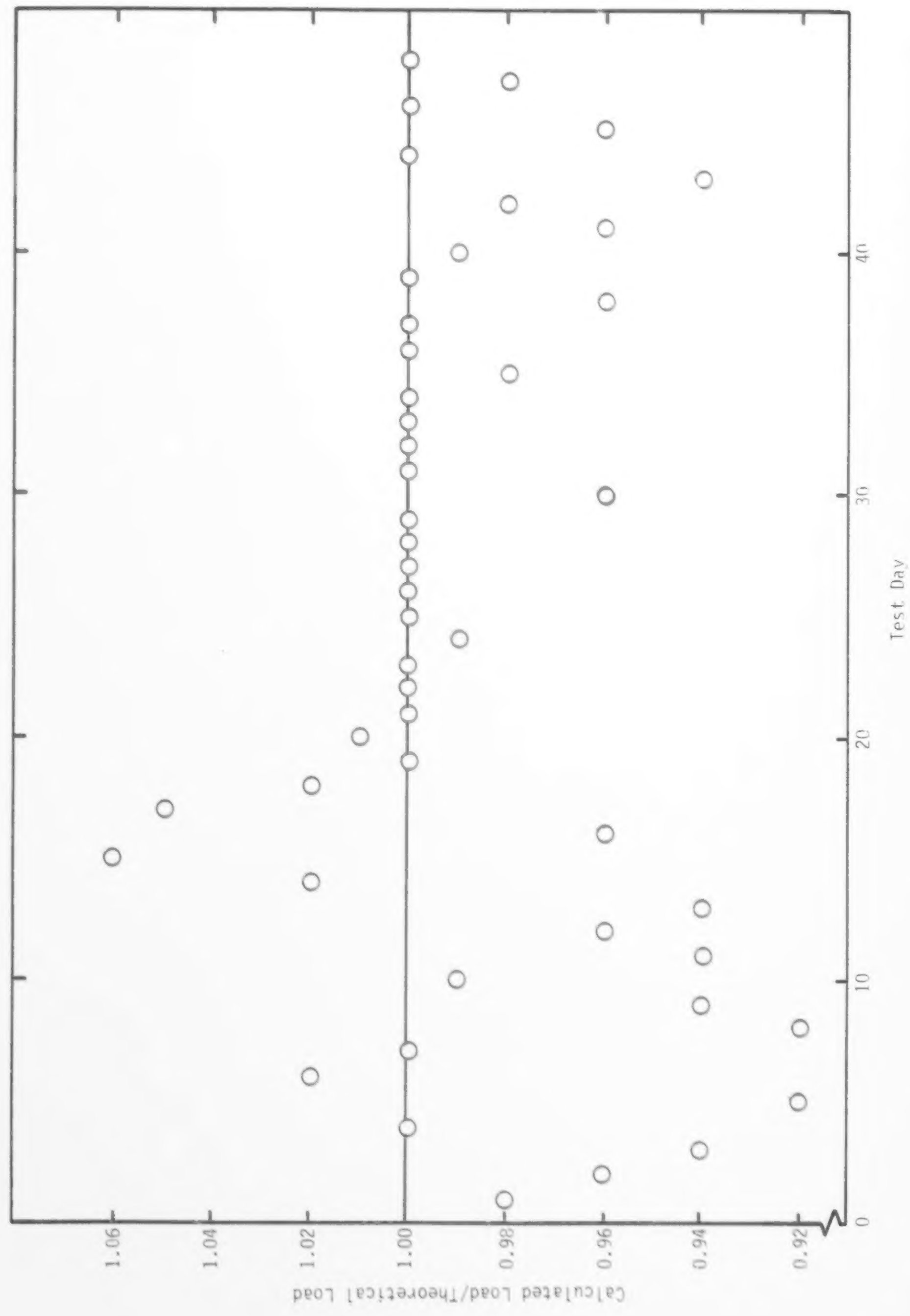

Figure B-5. Daily system check results.

MBtu/hr is shown in Figure B-6. Completion of this check confirmed furnace stability from day to day.

B.5.3 Coal Feedrate

The main coal feeder was calibrated by operating the feeder system at constant feed rate and determining the mass of coal collected in a measured time period. A calibration graph showing the mass flux of coal as a function of feeder speed setting was produced as shown in Figure B-7. Preground and dried coal was supplied to the feeder from large storage bunkers.

B.6 Quality Assurance Audits

B.6.1 Internal Audit

The internal system audit, performed by the quality assurance officer at EER, involved the review of sampling and analytical procedures with the measurement personnel, test equipment inspection, and the review of measurement and quality control documentation. The performance of the sampling system was checked by comparison of measured NO concentrations obtained by passage of a span gas through the span port and the sampling system. Results are shown in Table B-7. The results of the audit showed that the overall measurement quality was acceptable and no major quality problems existed.

B.6.2 Technical Systems and Performance Evaluation Audits by EPA

On July 17, 1985 an on-site technical systems audit and performance audit was conducted by Mr. Gary L. Johnson and Mr. Merrill Jackson of the EPA, and Dr. David R. Taylor and Mr. Larry E. Michalec of S-cubed. The purpose of the audit was to observe and document quality assurance and quality control procedures related to data generation, and to evaluate the extent of implementation of the Quality Assurance Project Plan (QAPP).

For the technical systems audit, a presentation was made to the auditors by EER which focused on the following topics:

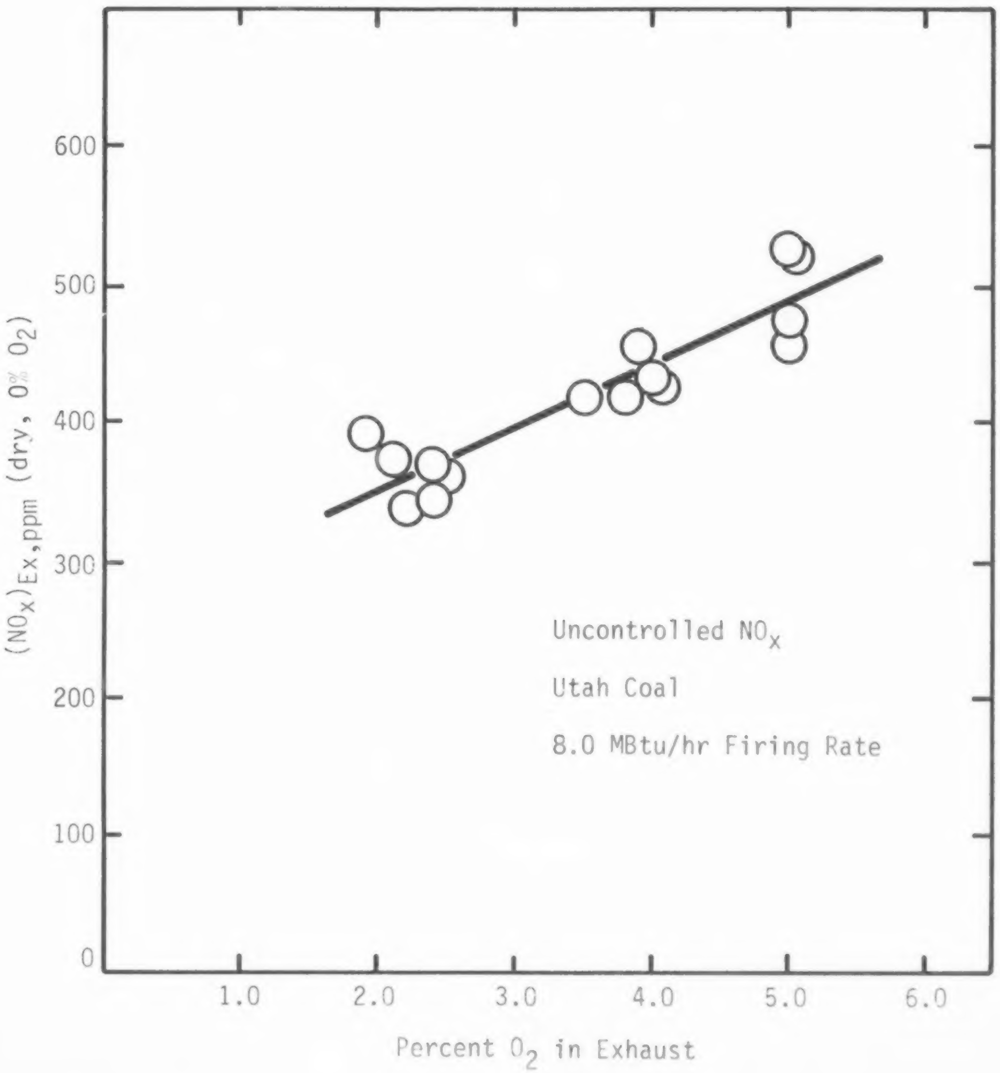

Figure B-6. Uncontrolled NO_x check.

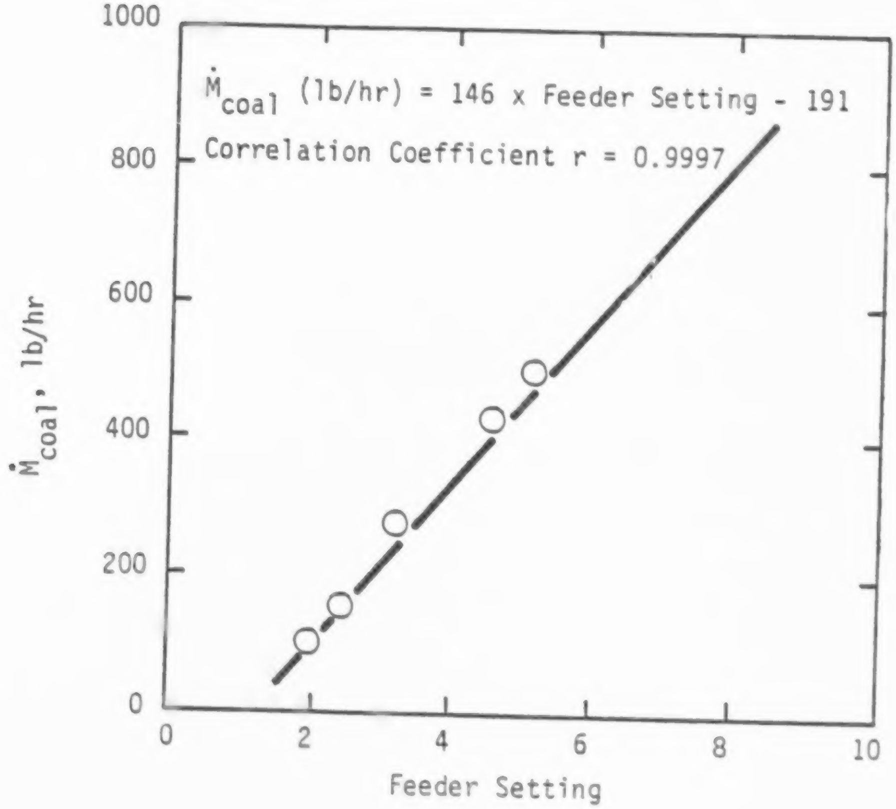

Figure B-7. Coal feeder calibration for Utah coal.

TABLE B-7. INTERNAL PERFORMANCE AUDIT OF GAS SAMPLING SYSTEM AND NO/NO_x ANALYSIS INSTRUMENT

Gas	Concentration (ppm) (Tank Certified Value)	Measurement Through Span Port (ppm)	Relative Accuracy	Measurement Through Sample Line (ppm)	Relative Accuracy
NO	191	188	1.6%	189	1.1%
NO	781	-	-	784	0.38%
NO_2	78	4 (NO Mode)	-	13 (NO Mode)	-
NO_2	78	81 NO_x Mode)	3.85%	74 (NO_x Mode)	5.13%

- The process of in-furnace NO_x reduction by reburning and how it may be applied to full-scale combustion systems.
- Evaluation of pilot scale reburning studies.
- Program objectives and responsibilities.
- A specific example of data reduction.
- Results of the EER internal systems audit.
- Definition of critical project measurements.
- Precision, accuracy and completeness measurements of analytical equipment used for the program. (See sections B.1 to B.3 of this chapter.)

Project documentation, including instrument calibration records, laboratory notebooks, operating procedures, quality assurance documents, data files, and instrument manuals were examined, and project personnel were interviewed to ensure that the QAPP was properly followed.

The purpose of the performance audit was to check the accuracy of the NO_x monitor and sampling system used in the reburning project. A zero air, and NO and NO_2 span gases of unknown concentrations were measured through both the span port, and sample line with the gas drawn into the system immediately after the sample probe. Results are presented in Table B-8. Another NO_2 span gas was measured, but its concentration was far beyond the scope of this program, thus the results were not reported.

The auditors concluded that the quality assurance/quality control program for the project was excellent, with only a few minor areas in need of improvement. The performance of the NO/NO_x analyzer was deemed good for measurement of the major parameter, NO. Instrument performance for the minor project parameter, NO_2, was termed erratic, but the NO_2 levels present under operating conditions were far less than that of the NO_2 span gas used for the performance audit (see Figure 3-5). After completion of the measurements, a

TABLE B-8. EPA PERFORMANCE AUDIT SUMMARY

Audit Gas Concentration (ppm)	Span Port Measured Concentration (ppm)	Instrument Stabilization Time (min)	Sample Line Measured Concentration (ppm)	Instrument Stabilization Time (min)
Zero Air* 6**	0	1	0	1
925 (NO)*	920 (NO Mode)	7	920 (NO Mode)	15
908**	930 (NO_x Mode)	2	945 (NO_x Mode)	2
192 (NO_2)*	5 (NO Mode)	1	25 (NO Mode)	3
180**	170 (NO_x Mode)	3	135 (NO_x Mode)	2
176***				
			10 (NO Mode)	4
			90 (NO_x Mode)	1

*Tank certified value.
**Method 7 analysis total NO_x.
***TECO Model 10 analysis total NO_x.

partial block of the NO_2 converter entrance was discovered. This blockage would cause results similar to those in Table B-8.

Because the overall QA/QC program was determined to be of very high quality, both audits were classified as "Acceptable." For a detailed account of the audits, refer to the report by Taylor, 1985.